THE DEVELOPMENT OF A MEASUREMENT SYSTEM FOR A MICRO GAS TURBINE

A DISSERTATION PRESENTED TO

THE SCHOOL FOR COMPUTER AND ELECTRONIC ENGINEERING

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POTCHEFSTROOM CAMPUS

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In Computer and Electronic Engineering

by

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Soli Deo Gloria

"To God alone the glory"

Summary

Gas turbines are widely used for jet engines, but also for power generation, especially in mobile applications such as aircrafts and ships. The need exists at the North-West University for the development of a micro gas turbine test system, as well as support documentation that supports the system. This facility and the support documentation will be used by the university for educational and research purposes.

This project is thus the development of a gas turbine measurement system. This system should be able to measure specific parameters of the gas turbine engine at specific locations. This measured data can then be used to characterize the gas turbine engine according to the Brayton cycle.

Similar systems are available at high cost. The aim is to develop this system at a reduced cost, without limiting the features and usability of the system. The system can then be integrated with Flownex®, a thermal-fluid network analysis package, where the results between a Flownex® simulation and the actual system can be verified.

Thirteen sensors, including temperature, pressure, thrust, speed, and fuel flow are implemented to measure the data at specific locations in the gas turbine engine. The data is shown in real time on a PC and on the control panel. The PC records the data for later analysis.

A systems engineering approach was followed throughout the design process. A very important contribution of this work is a functional analysis done on the complete system to ensure functional capability of the system. A functional analysis, as will become clear from this work, simplifies and accelerates the development process since it combines all aspects of the design.

An optimal design was required. Therefore, attention was given to design for safety, electromagnetic compatibility (EMC), maintainability, affordability, and usability during the design phases.

Opsomming

Gas turbines word algemeen gebruik in straalvliegtuie, maar ook vir kragopwekking, veral in mobiele toepassings. Die behoefte bestaan by die Noord-Wes Universiteit om 'n toets-stelsel, sowel as steundokumentasie, te ontwikkel vir 'n mikro gas turbine. Hierdie stelsel en steundokumentasie kan gebruik word vir akademiese, sowel as navorsingsdoeleindes.

Hierdie projek bestaan uit die ontwikkeling van 'n gas turbine meetstelsel. Spesifieke parameters van die gas turbine enjin moet gemeet word op spesifieke posisies op die gas turbine. Die gemete data kan dan gebruik word om die stelsel te karakteriseer volgens die Brayton siklus.

Soortgelyke stelsels is beskikbaar teen hoë koste. Die doel van hierdie projek is om 'n soortgelyke stelsel te ontwikkel teen 'n laer koste, sonder om die funksionaliteit en bruikbaarheid van die stelsel te affekteer. Hierdie stelsel kan ook geïntegreer word met Flownex®, 'n termodinamiese netwerk analise pakket, waar die resultate tussen 'n Flownex® simulasie en die geïmplimenteerde stelsel vergelyk kan word.

Dertien sensors is geïmplimenteer om data op spesifieke stadiums van die enjin te meet. Dit sluit in: temperatuur, druk, spoed, stukrag asook brandstofverbruik. Die data word intyds op die beheerpaneel en op die rekenaar vertoon. Die data word dan ook geberg sodat dit ge-analiseer kan word.

'n Stelsel-ingenieurswese proses is gevolg gedurende die ontwerp van die stelsel. 'n Belangrike bydrae van hierdie werk is 'n funksionele analise wat uitgevoer is op die stelsel in geheel om die funksionele bevoegdheid van die stelsel te verseker. 'n Volledige funksionele analise, soos dit duidelik word uit die werk, vergemaklik en versnel die ontwikkelingsproses aangesien dit alle fasette van die stelsel saamvat.

'n Optimale ontwerp was benodig, daarom is aandag gegee aan veiligheid, elektromagnetiese versoenbaarheid, onderhoubaarheid, bekostigbaarheid asook bruikbaarheid gedurende die ontwerpsfases.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

ADM	Advanced Development Model
BIT	Build in Test
CAD	Computer Aided Design
CCP	Capture Compare PWM
DUT	Device Under Test
EDM	Engineering Development Model
EGT	Exhaust gas temperature
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
F/U	Functional Unit
GUI	Graphical User Interface
HAL	Hardware Abstraction Layer
I/F	Interface
IC	Integrated Circuit
I/O	Input / Output
kPa	kilopascals
LCD	Liquid Crystal Display
M/F	Maintenance Function
MCU	Microcontroller Unit
O/F	Operational Interface
PCB	Printed Circuit Board
PPP	Pre-Production Prototype
PSI	Pounds per Square Inch
PSU	Power Supply Unit
PWM	Pulse Width Modulation
RAM	Random-access Memory
RF	Radio Frequency
RPM	Revolutions per Minute

SCU	Safety Control Unit
UART	Universal Asynchronous Receiver-Transmitter
XDM	Experimental / Exploratory Development Model

Chapter 1
Introduction

1.1 Background

The gas turbine is a power plant, most commonly used for jet engines, mainly because it produces a great amount of power compared to its size and weight. Increased use has been found for gas turbines over the past 40 years in the power plant industry and therefore the gas turbine technology has grown exponentially over the past few years [15].

One of the main reasons that led to the growth in gas turbine technology is the growth of material technology, new coatings, as well as new cooling schemes. This, in conjunction with an increase in compressor pressure ratio, has increased the gas turbine thermal efficiency from about 15% to over 45%.

The gas turbine is used in a variety of applications. This includes electric utilities like stationary power generation plants and mobile power generation engines that are mainly used in ships and aircrafts.

1.2 The Purpose of the Research

The primary purpose of this project is to:

Develop a micro gas turbine experimental system that can be used to characterize a gas turbine by analyzing physically measured data.

This facility can then be integrated with Flownex® in a further study while it can also be used by the Mechanical Engineering Faculty of the North West University to assist the students in their studies, especially in the field of gas turbines. The students can use this facility to execute practical experiments and broaden their knowledge regarding gas turbines.

Similar experimental facilities do exist, but are they expensive. The aim of this project will be to develop a facility at a fraction of the cost without reducing the functionality of the system. The high cost of the existing system is mainly due to expensive data acquisition systems that are used in the existing system. A less expensive (but effective) approach will be followed in this project. The existing system is also more costly since economy of scale does not hold for this type of system (a small number of systems are sold).

1.2.1 System Layout

The layout of the system is shown in Figure 1.2.1. This figure shows the gas turbine test bench that interfaces with a PC and operated by an operator.

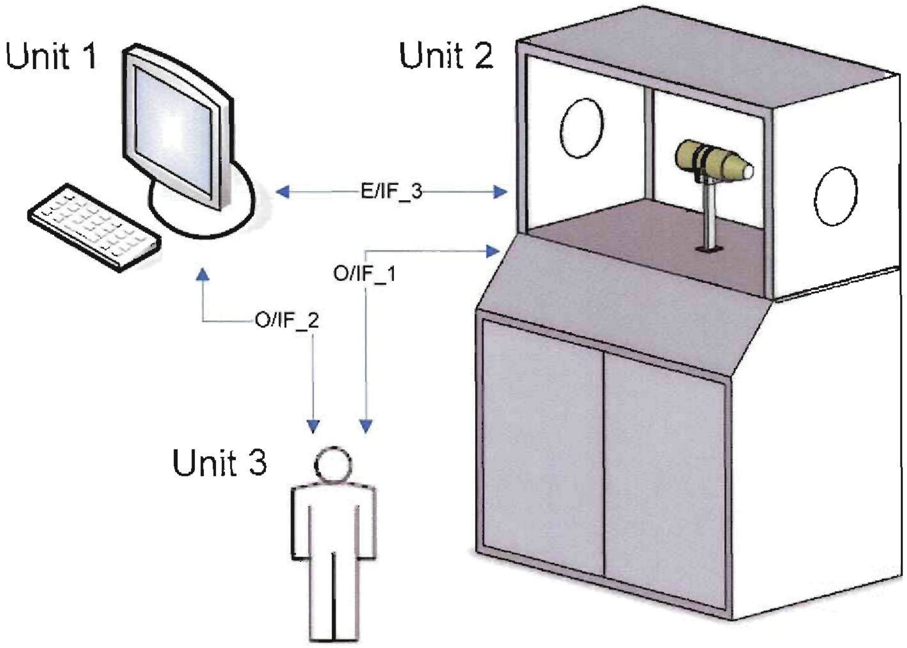


Figure 1.2.1 System Layout

The descriptions for the above mentioned units are as follows:

1. The PC is used to log all the data from the gas turbine test bench. The logged measurements include speed, pressures, temperatures, thrust, and fuel consumption. The data needs to be displayed in real time and can be saved for analysis afterwards.

2. The gas turbine test bench consists of the gas turbine engine, interfacing with all the required sensors, electronic circuitry, and control panel.

3. The operator can operate the gas turbine engine via the control panel on the test bench. An automatic startup procedure should be implemented to start the engine by the press of a button. After startup, the turbine can then be safely controlled with a speed control dial.

1.3 Issues to be Addressed and Research Methodology

The development process of a gas turbine facility is divided into two parts, namely a mechanical and an electrical / electronic section. This document focuses on the electrical / electronic part. The mechanical part shall consist of the mini-dissertation of Mr. J.S. Oosthuizen, a B.Eng student in the School of Mechanical Engineering.

A basic graphical representation of the project scope regarding the electrical / electronic part is shown in Figure 1.3.1. The figure shows the scope in a workflow format.

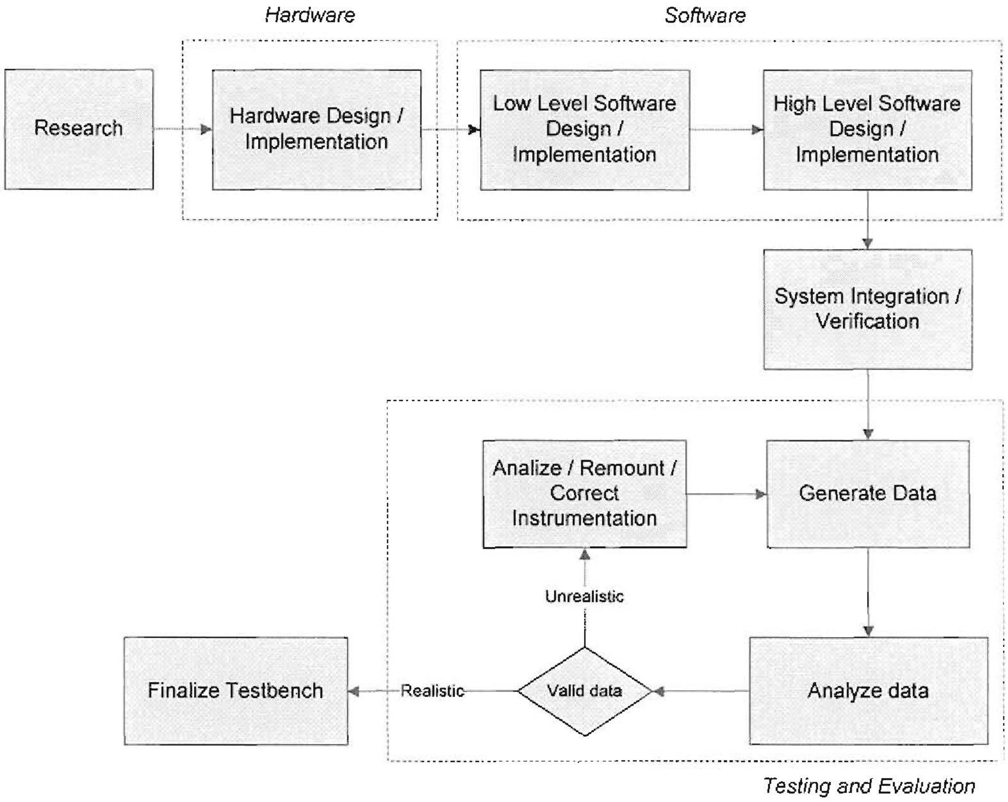


Figure 1.3.1 Project Scope Workflow

A systems engineering approach was followed throughout the development of this gas turbine measurement system. A detailed functional analysis was performed during the preliminary design phase in order to define the *fit*, *form* and *function* of the system.

It is imperative to realize that a functional analysis is the main differentiator between systems engineering and other forms of specialty engineering. A functional analysis provides an abstraction of the overall system – this is usually not done when following a "bottom-up" approach. In addition, a functional analysis provides the following very important advantages:

- All system functions are defined in terms of a functional flow and architecture, from operational level down to detail technical level - function;
- All interfaces are identified and defined. This includes interfaces between users (such as operators), equipment, facilities, and even software - fit;
- A definition of the system architecture provides an abstract framework for all detail architectures, which may also include software – form.

Electronic circuitry was designed to capture all measurements, control the turbine, and display all measured data and derived information. An Experimental Development Model (XDM) was implemented first. This design includes all the necessary inputs and outputs as well as a communication interface with the PC. After this XDM had been implemented, the design was optimized to result in an Engineering Development Model (EDM). This electronic circuitry was laid out on PCB's and implemented for the final integration of the system.

An advantage of following a systems engineering approach is that concurrent engineering becomes possible since the system structure is known from the concept onwards. In this case, the advantage was that one "usually" necessary phase, the Advanced Development Model (ADM) phase, could be bypassed.

Separate modules were implemented to optimize the design as a measurement system. This was done by following EMC and other design guidelines. These guidelines are also a result of following a systems engineering process.

Firmware was designed, programmed, and implemented on electronic modules of the system. The programs ensured that measurements could be read while control was exercised over the turbine and all communication between different modules was handled.

High-level software was developed for a PC to record and display data from the gas turbine engine. This data is available for later analysis, and may also be imported into an analysis program for later use.

The system was tested and verified as a complete unit by referring to the functional requirements as defined in the functional analysis. The availability of a functional definition enables the designer to test and verify against a set structure. Data was generated and analyzed to ensure that the system provided the required functional capability.

1.4 Overview of the Dissertation

Chapter 2 consists of a literature study where an overview of the existing MiniLab Gas Turbine Power System is provided together with the objectives for the development of a gas turbine facility. Existing shortfalls of the MiniLab system are discussed. The design philosophy is based on the systems engineering approach - this approach is discussed with "design for" criteria such as electro-magnetic compatibility etc. These guidelines must always be followed throughout the preliminary and detail design phases.

The background regarding gas turbines is discussed with focus on the analysis of the Brayton cycle, followed by an overview of sensors that were required for this measurement system. The chapter is concluded with detail regarding instrumentation and possible implementation options that can be considered.

The preliminary design is given in chapter 3. The chapter focuses on a functional analysis of the system. First, an operational analysis is done in the form of functional flow to determine the *function* and *fit* of the system. The functional analysis also consists of a system architecture. This architecture is broken down into sub-levels to provide more detail. All interfaces of the architecture are defined. The functional analysis is concluded with a resource allocation where all the functional units are mapped to operational functions. At the end of this chapter, design guidelines for this design are given. Amongst others, the ground layout of the system is shown with the location of key modules, as defined in the functional analysis.

Chapter 4 comprises the detail design phase. Since this document also serves as a detail design description, special attention is given to all detail elements, however repetitive and obvious this may seem. The Experimental / Exploratory Development Model (XDM) is discussed first, followed by all sensors used for the system, together with the driving and measurement details of these sensors.

The Engineering Development Model (EDM) is treated next. Here, the implementation for each module is discussed separately. Attention is given to the ground layout of each PCB to optimize the design for EMC for a robust measurement system. The firmware and software design are shown in state diagrams, together with the implementation of the Graphical User Interface (GUI) that is used to log and display measurement data in real time.

Testing and verification are done in chapter 5. Here, results from tests on the system's sensors are given as verification. The verification data of the system is shown in graphical format. The system was also tested as a complete unit and the performance of the PC software was determined – these results are also given in chapter 5.

Finally, the conclusion of the project is provided in chapter 6, with future work that can be done on this project.

Chapter 2
Literature Study

2.1 Introduction

The aim of this chapter is to provide the reader with background regarding this project, and in particular gas turbine engines. This background includes a discussion on an existing alternative to this system, a design philosophy that was followed throughout this project, gas turbine theory, and possible instrumentation solutions.

The chapter starts with an overview of an existing system - the MiniLab Gas Turbine Test Bench is discussed. The need for the development of this gas turbine test facility, together with the shortfalls of the existing system is discussed. Thereafter, the design philosophy is discussed where the systems engineering life cycle is overviewed. This section also includes design criteria and guidelines that should be followed in order to design for electromagnetic compatibility (EMC), manufacturability, maintainability, usability, safety, and affordability. Gas turbine theory is discussed where the Brayton Cycle is analyzed together with required parameters that should be measured in this measurement system. Possible solutions for the instrumentation that can be used to measure this data conclude this chapter.

2.2 Overview of existing systems

2.2.1 The MiniLab™ Gas Turbine Power System

The MiniLab Gas Turbine Test facility is available from Turbine Technologies [1], as shown in Figure 2.2.1. This facility is designed for education in the engineering, technical and military fields, and also for advanced research and study of thermodynamics and the operating principles of gas turbine engines.

Figure 2.2.1 The MiniLab Test Facility [1]

This test facility is equipped with 13 sensors to measure temperatures, pressures, thrust, speed, and fuel flow. The temperature and pressure sensors are located at key positions – the measurements are displayed on the control panel. The measured data is also shown in real time in graphical format on a PC. The system can be operated via the auto start feature. The electronic control circuitry is also equipped with necessary safety features, and will shut the system down in an emergency.

The MiniLab Gas Turbine Test facility makes use of an SR-30 engine. This engine is also designed and manufactured by Turbine Technologies. It consists of an inlet nozzle, centrifugal compressor, an annular reverse flow combustion chamber, an axial flow turbine and a thrust nozzle. The SR-30 engine can produce up to 18kg (178N) of thrust, measured by a pivot bearing arrangement that utilizes a calibrated load cell. All the required fittings for the sensors and instrumentation are fitted on this engine when it is manufactured by Turbine Technologies [1].

2.3 Objectives of a General Gas Turbine Test Facility

The objectives for a Gas Turbine Test Facility are as follows:

- To provide a research facility;
- The application of fluid, thermodynamic, combustion and gas turbine theory to the operation of an actual engine;
- Measurements are displayed in real time;
- Measurements are logged for further analysis;
- Further possible calculations can be done from the measured values:
    - Compressor Analysis – compressor pressure ratio, power required, and compressor efficiency;
    - Turbine Analysis – work and power developed, expansion ratio and turbine efficiency;
    - Brayton Cycle Type Analysis – mass flow rate, inlet and exit velocity, station temperature and pressures, combustion and thermal efficiency, specific fuel consumption and power / thrust developed;
    - Combustion analysis and general analysis – excess air and fuel air ratio
    - General Analysis – diffuser and nozzle performance and efficiency;
- Educational: Students get motivated when they see how gas turbines work in practice.

2.4 Shortfall of the Existing System

The existing MiniLab system from Turbine Technologies meets the technical requirements for such a test facility. The main factor is cost. The MiniLab system from Turbine Technologies costs approximately $52 448.69. This is equivalent to R393 365.17 (with a foreign exchange rate of $1 = R7.5).

Furthermore, the existing system cannot be easily integrated and controlled by Flownex®. Although this is not a primary requirement, the flexibility that comes with software and hardware ownership is a secondary requirement that is not addressed by the MiniLab system.

Therefore, a decision was made to design and build a similar system at reduced cost. This unit shall be used at the North-West University for educational purposes.

2.5 Design Philosophy

The design philosophy of this project is simply to follow a complete systems engineering approach. This is a technologically based interdisciplinary process for bringing systems, products, and structures (human-made entities) into being [2]. One of the main advantages resulting from using systems engineering is to shift the focus from the design entities themselves, and rather concentrate on what the entities should do before determining what they are. Therefore, the *form* should follow *function*.

The final product of systems engineering is an engineered product. The main goal of this approach is to design human-made entities to satisfy human needs and/or objectives effectively while minimizing system life-cycle cost, and the costs of ecological and societal impacts [2].

Not many texts on applied systems engineering exist since most of this information is classified. That is, successful applications of systems engineering are usually so valuable that the actual case study is not available. A secondary result from this work is to provide support data (in the form of this document) that can be used to train future systems engineers, as well as data that will support this system in the future.

The systems engineering approach that was followed throughout this project is discussed in the following section.

2.5.1 Systems Engineering Life-Cycle

The systems engineering life-cycle is shown in Figure 2.5.1. Each block is explained in detail in the following paragraphs.

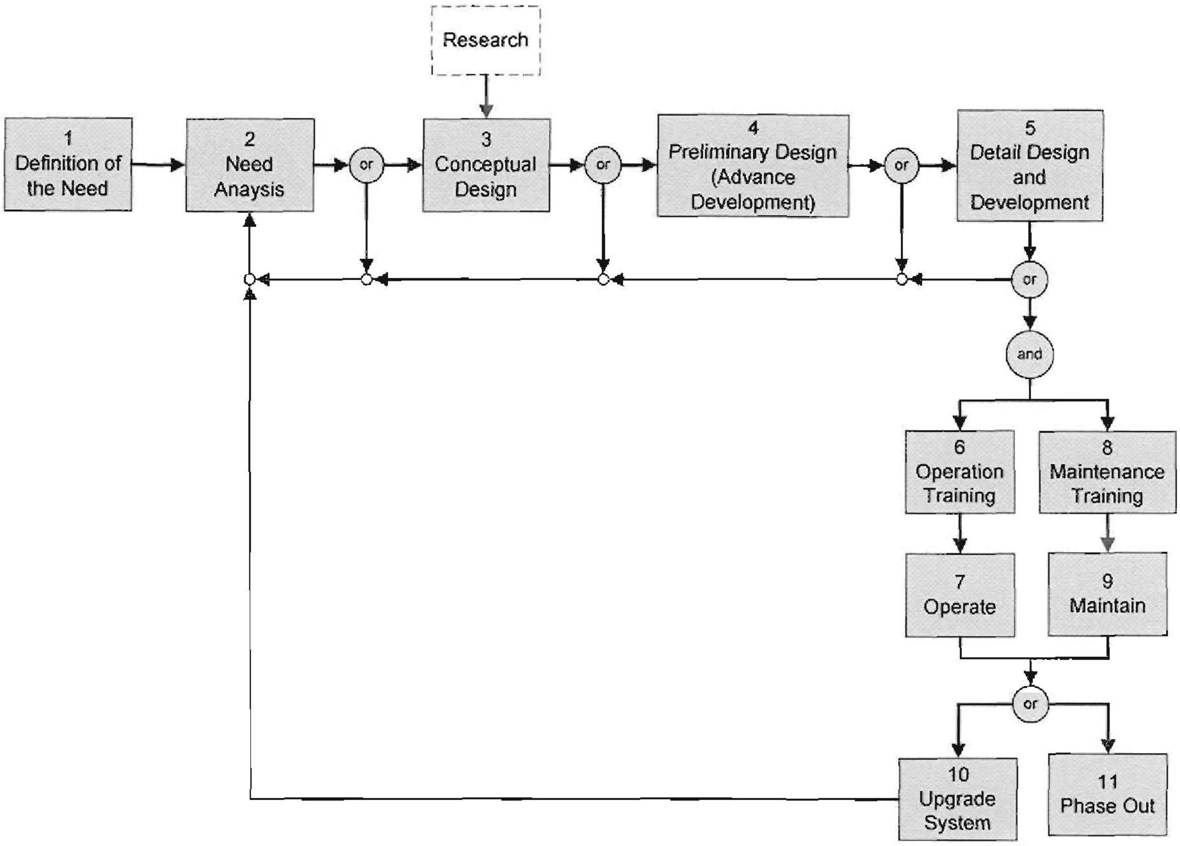


Figure 2.5.1 The Systems Engineering Life Cycle [2]

2.5.1.1 Definition of Need

Firstly, the necessity of the product should be defined by the customer. There may be numerous factors, such as system size and weight, system performance, operational availability, reliability and maintainability, supportability, cost, etc [2].

2.5.1.2 Need Analysis

The need should be analyzed to determine if it is worthwhile to develop a system. For instance, suppose that a current system capability is not adequate in terms of meeting certain required performance goals, is not available when needed, cannot be properly supported, or is too expensive to operate. Or there is a lack of capability to communicate between two specific points, at a specified rate, with a specific desired reliability, within a specified cost. As a result, a new system requirement should be defined [2].

2.5.1.3 Conceptual Design

The conceptual design is the most important phase of the system design and development process. This early and high-level life-cycle activity has the potential to establish, commit and predetermine the function, form, fit, cost, and development schedule of the desired system.

The following procedures should be followed in the conceptual design phase:

- System operational requirements such as system functional capability and other requirements such as environmental, physical, legal etc;
- System maintenance concept to include maintenance and repair policies and support logistics;
- Lower-level functional requirements that follow from the operational requirements;
- Advance product planning (plans and specifications) [2].

2.5.1.4 Preliminary Design (Advance Development)

The purpose of the preliminary design phase is to demonstrate that a selected system concept will meet performance and design specifications and that it can be produced with existing methods within established cost and schedule constraints.

This is a neglected phase in development processes. Specific attention shall be given to preliminary design since it is a secondary objective of this work to demonstrate the effectiveness of this phase.

Figure 2.5.2 shows the preliminary design phase broken down into sub sections. The procedures to be followed in each of these sections are discussed:

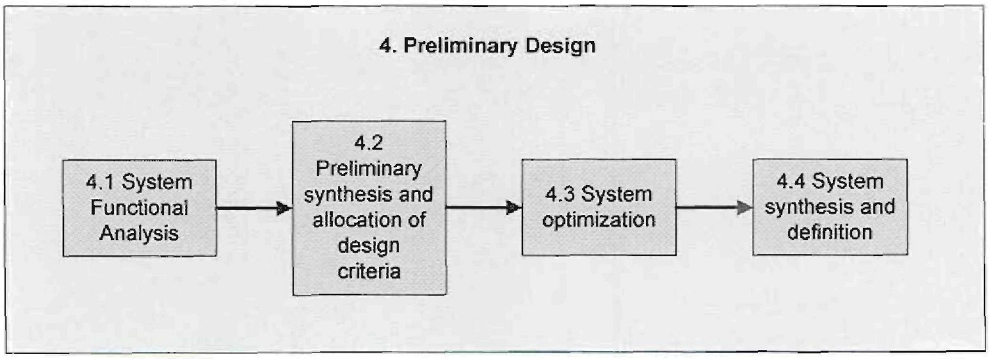


Figure 2.5.2 The preliminary design phase [2]

System Functional Analysis

A functional analysis lies at the core of systems engineering. This analysis draws together all elements of a system and provides important information that is used for (i) the establishment of functional capability, (ii) identification and definition of maintenance functions, (iii) identification of test requirements, (iv) identification of critical functions and fault analysis, (v) identification of interfaces, and (vi) allocation of performance and design requirements, amongst others. Indirect results from a functional analysis include assembly / manufacturing data (from the systematic break down of an architecture), operator procedures and manuals, repair procedures, and other data that can be linked to functions and architecture.

A particularly neglected advantage of a functional analysis is the identification and design of user functions and interfaces. In practice, it is not uncommon for engineers to design equipment and machines that expect a user / operator to adapt to the system, instead of the system being adapted to the user [27]. A functional analysis that focuses on usability will identify all functions that a user will execute and provision will be made in the design to simplify these functions. Interfaces are simplified in the same fashion.

The steps that are followed to perform a functional analysis include:

- Functional analysis;
    - System operational functions;
    - System maintenance functions;
    - System architecture;
- System analysis – identification of alternative functions and sub-functions.

Preliminary Synthesis and Allocation of Design Criteria

Performance and design criteria are linked to functions and functional units. Each function should have its own performance requirements, while design criteria are usually linked to functional units (architecture – the assemblies, sub-assemblies, components and interfaces of a system).

Important aspects of an allocation include:

- Allocation of performance factors, design factors and effectiveness requirements;
- Allocation of resources to functions (“design”, in the classical sense);

- Allocation of system support requirements;
- System analysis.

A resource allocation links functions to resources and provides a means to do failure-mode analysis. Each resource failure affects functions at different levels – these may be identified from the resource allocation table.

System Optimization

During design, different architectures are considered as solutions to the system functional requirements. An abstraction is usually done to provide an interim framework for later use in trade-off studies. This means that an abstracted functional unit can be realized by using different technologies or resources. The selection of the best solution for a functional unit results in optimization of that functional unit.

Important aspects of system optimization are:

- System and subsystem trade-offs and evaluation of alternatives;
- System and subsystem analysis.

System Synthesis and Definition

An aspect of design that is not always obvious, is the fact that a system definition (captured in a specification) is not always available at the onset of design. This means that the detail specifications must sometimes be "developed" by first developing an Experimental / Exploratory Development Model (XDM). Tests are usually performed on the XDM in order to define the performance boundaries / limitations of a specific technology or solution (including humans). This implies that, before a preliminary design is started, there may have been extensive conceptual development.

System synthesis and definition includes:

- Preliminary design to include performance, configuration, and arrangement / architecture of the selected system;
- Drafting of detail / development specification(s) [2].

2.5.1.5 Detail Design and Development

In the detail design and development phase, the system configuration focus shifts to more specific components down to the lowest level in the hierarchy. This includes the accomplishment of activities that describe sub-systems, units, assemblies, lower-level components, software modules, people, facilities, elements of maintenance and support, etc that make up the system and address their interrelationships. Here, specifications and design data for all system components are prepared, while the selected components are acquired and integrated into a final system configuration.

A breakdown of the detail design and development phase is illustrated in Figure 2.5.3. The procedures that need to be followed are as follows:

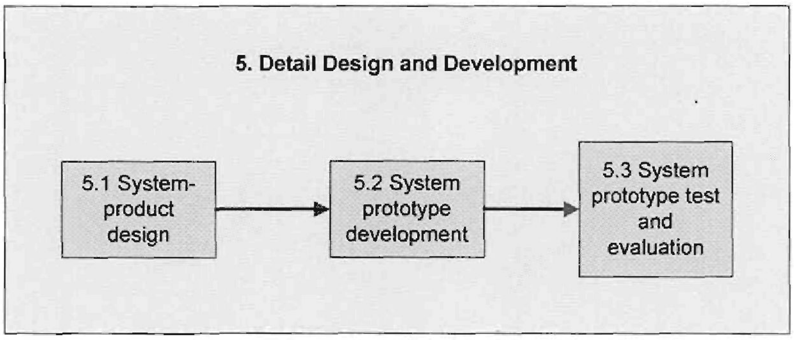


Figure 2.5.3 The detail design and development phase [2]

System-Product Design

- Detail design of the functional system. This includes software / firmware design and detail electrical / electronic design;
- Detail design of maintenance and logistic support elements. The high-level functional analysis indicates maintenance and logistics support elements to a large extent;
- Design support functions provided by the manufacturers of technology or software / firmware development tools, amongst others;
- Design data and documentation such as the availability of design data, publication of case studies, design notes and statistical data, and software / firmware support tools, and other data;
- System analysis and evaluation. This includes all testing, analysis and evaluation of test results;

- Design review to consider successes and possible adjustments (that may result in the adaptation of higher-level specifications).

System Prototype Development

It is not always evident, but detail design may actually be made up of different phases. It is helpful to use XDM (Exploratory Development), ADM (Advanced Development), EDM (Engineering Development) and PPP (Pre-Production Prototyping) as standard development phases. A final Prototype is the result of system prototype development.

In the electronic product development environment, most of the above phases are executed in an iterative fashion. XDM's are very much "experimental" and may even include simulated models. XDM's are sometimes developed during the concept design phase, but may also be developed in the detail design phase if the system is complex. An XDM is used to prove only the functional feasibility of the system.

ADM's are used to provide first form of a system or product. In the case of electronic product design, this could be the first layout on PCB to fit inside a mock-up or rapid prototype enclosure. An ADM shows the form so that mechanical / physical constraints may be tested. It is also helpful to consider EMC requirements in this phase since it could reduce development time significantly. It is possible to use CAD modeling to ensure mechanical fit, with the result that this phase may sometimes be bypassed.

An EDM is used mainly for testing. This is a model that has addressed all form, fit, and function requirements and should be submitted to test facilities for compliance / performance testing. If planning has been done properly, it is usually the case that the first enclosures (for instance, when injection molding was used) become available during this phase, so that mechanical fit can be tested.

A PPP is used to test and prove the manufacturability of a product. At this stage, test equipment have been designed and implemented (such as jigs and software). The focus during this phase is thus on manufacturing support and effectiveness.

All maintenance requirements must have been addressed at this stage, as well as all logistic support, manufacturing (including packaging), and logistics.

Thus, the main aspects of prototype development include:

- Development of interim development models (XDM, ADM, EDM, and PPP). Some models may be skipped if the minimum requirements for a model have been met in the design;
- Development of a final system prototype model;
- Development of system maintenance and logistic support requirements.

System Prototype Test and Evaluation

When proper planning was done and the preliminary design phase resulted in good test requirements, the following steps characterize system test and evaluation:

- Test preparation to include test sheets, support equipment, and logistics planning;
- Testing of prototype system and equipment. This may take place at a third-party facility such as a test laboratory, or may be a field test;
- Test data, analysis, and evaluation;
- Test reporting;
- System analysis and evaluation. This may result in the adjustment of higher-level specifications – a process which is costly and not desirable;
- Modifications for corrective action.

Hereafter the system is used for the need and also needs to be maintained, therefore training is an important consideration. Thereafter the system can be upgraded or, when the system is no longer needed, the system reaches the phase out or disposal phase [2].

2.5.2 "Design for" Criteria

There are important aspects to take into consideration when designing an electronic system. During the preliminary design phase, all "design for" criteria for a specific system or product must be defined. This is used to guide detail designers through the detail design process to ensure quality.

The design criteria that will guide the design of the development of a Gas Turbine Measurement System are discussed next.

2.5.2.1 *Design for EMC (Electromagnetic Compatibility) [3]*

Electromagnetic interference (EMI) is a serious form of environmental pollution. This pollution is also increased by the daily increase of electronic systems in the society. The effects of EMI can be anything from minor annoyances such as crackles on broadcast reception, to fatal accidents due to corruption of safety critical control systems.

Below follows a list of guidelines from [3] that should be used when designing for EMC. Only guidelines applicable to this project are discussed.

1. Design for EMC from the beginning while knowing the required performance;
2. Split the system into critical and non-critical sections:
    a. Determine the noise and susceptible circuits;
    b. Lay these circuits out in separate areas from the non-noisy circuits;
    c. Internal and external interface points should be selected to allow optimum common mode current control.
3. Keep EMC in mind when selecting components and circuits:
    a. Use slow, high-immunity logic as far as possible;
    b. Apply slew rate limiting to data transmission interfaces (typically RC filters);
    c. Efficient RF decoupling techniques should be followed - capacitors as close as possible to ICs. R and L filters can also be used in the power supply line for decoupling;
    d. Fan-out should be reduced on the clock circuits by liberal use of buffers;
    e. Minimize the bandwidth of signals, while maximizing output levels;
    f. Verify stability in wideband amplifiers;
    g. Use resistive, ferrite or capacitive filtering techniques at all sensitive analogue inputs;
    h. Use watchdog circuits on microprocessors.
4. PCB layout:
    a. Proper signal returns should be implemented;
    b. Keep interface paths away from sensitive circuits while incorporating a ground plane for the interface;
    c. The ground inductance should be minimized by using one or more ground planes;

- d. The high current enclosed loops should be minimized to a minimum area together with the high Δi/Δt and sensitive circuits;
- e. The surface areas of the nodes with a high Δv/Δt should be minimized;
- f. Don't leave any floating conductor areas by making sure that copper areas are connected;
- g. Minimize the length of tracks and component lead outs;
- h. Place filters as close as possible to their interfaces, with critical circuits away from ground plane edges.

5. Cables:
    - a. Do not run signal cables parallel to power cables;
    - b. Use signal cables and connectors with the required screening;
    - c. Use twisted pair if appropriate, especially for high Δi/Δt lines;
    - d. Cables should be run away from apertures in the shielding, close to the conductive grounded structures;
    - e. Resonant lengths should be avoided as far as possible. Consider damping cables with ferrite suppressors;
    - f. Ensure that the screens of the cables are properly terminated to the appropriate connector, while avoiding pigtails;
    - g. Lines carrying high frequency signals should be terminated with the correct impedance.
6. Grounding:
    - a. The ground system should be designed and enforced at the product definition stage;
    - b. Consider a ground system as a return current path instead of a 0V reference;
    - c. Ensure sufficient bonding of screens, connectors, filters, cabinets, etc;
    - d. Make sure that the bonding will not deteriorate in harsh environments;
    - e. Use masks for paint from any intended conductive areas;
    - f. Earth leads should be kept short while defining their geometry;
    - g. Common ground impedances should be avoided;
    - h. A "clean" ground area should be provided for the decoupling of all interfaces.
7. Filters:
    - a. The mains filter should be optimized for an application;
    - b. I/O lines can be filtered by using a combination of capacitors to the quiet, low-impedance ground together with common mode chokes;
    - c. PI filters can be applied at the power input at each board;

   d. Ensure a good ground return for each filter;
   e. Filtering to interface sources should be applied, such as switches and motors.
8. Shielding:
   a. The type and extend of shielding required from the frequency range of interest should be determined;
   b. Extra internal shielding can be used to enclose particular sensitive or noisy areas;
   c. Large or resonant apertures should be avoided in the shield, or measures should be taken to mitigate them;
   d. Ensure good bonding of the separate panels down their seams.
9. Test and evaluate for EMC continuously throughout the design process.

2.5.2.2 Design for manufacturability [2]

In order to make the system reproducible, design for manufacturability needs to be taken into consideration. This means that the design should be optimal, producible, and testable. All these should be considered in the design process. This system does not require extensive provisions for manufacturability. Therefore, less focus is placed on this requirement. However, component availability and support were considered in the selection of components and units.

In order to design for manufacturability, the following design guidelines need to be followed:

1. Supply support:

   This includes spare part, consumables, special supplies, software modules, and supporting inventories required to manufacture and maintain the system. These items should be easily accessible for manufacturing and therefore should widely available components, from trusted suppliers be used.
2. Testability:

   Al the test equipment should be available and known together with the testing procedures. Diagnostic test should also be incorporated within the system design.

2.5.2.3 Design for maintainability

This "design for" criterion ensures that the system is maintainable during its life cycle. This is the ability of the system to be serviced, repaired, and returned to service rapidly and efficiently in order to increase the lifetime of the system. This also enables other parties, apart from the original designers, to be able to maintain the system, if possible. Some guidelines to be followed are explained next.

Hardware

1. Use well known, commonly available components as far as possible;
2. Make sure effective components are used, from a globally known, trusted supplier;
3. Use widely available CAD tools for design and PCB layout;
4. Document any physical design changes or modifications if a newer version is not laid out on a PCB.

Software and firmware [4]

1. Portability
    a. Use a consistent style to make the code portable to other compilers;
    b. Create an abstraction level by deriving code from higher-level functional analyses.
2. Readability
    a. Construct a functional design document to represent the code;
    b. Use a documented introductory comment that provides information of the file and its contents;
    c. Write descriptive comments before every function or procedure;
    d. Comment code lines as often as possible;
    e. Choose proper descriptive names for variables and functions.
3. Construction
    a. Implement user interfaces from the conceptual design;
    b. Keep structures separate.
4. Traceability
    a. Use a documented design methodology;
    b. Make use of well known compilers and CAD tools;
    c. Link each section of the source code to the functional analysis of the system;
    d. Always give a file a name that unique in the context.

2.5.2.4 Design for usability [2]

The requirements for the human, as part of the system design, are initially derived through the definition of the system operational analysis, together with the maintenance concept. The human requirements should consider the following factors:

1. Anthropometric factors:

   This involves the consideration of the physical dimensions of the human body. The weight, height, arm reach, hand size, etc. are critical when designing operator stations, control panels, accesses for maintenance purposes, and the like.
2. Human sensory factors:

   One should be aware of certain human sensory capabilities when dealing with human-machine interface designs. This consists of vision, hearing, smell, feeling, balance, etc. Factors pertaining vision and hearing are of particular significance.
3. Physiological factors:

   Environmental stresses on the human body should be taken into account while designing a system. Some of the causes for stress are temperature extremes, humidity, vibration, noise, gas or toxic substances in the air, radiation, etc.

2.5.2.5 Design for safety [2]

The following guidelines should be followed when designing for safety.

1. Describe hazardous areas;
2. Explain possible causes of hazards;
3. Identify hazard effects;
4. Classify hazards;
5. Estimate the probability of hazard occurrence;
6. Describe actions that can be taken to eliminate or minimize the hazards.

2.5.2.6 Design for affordability [2]

Many systems are planned, designed, produced, and operated with little initial concern for affordability of the total cost of the system or the intended life cycle. In order to address the cost factor efficiently, a life cycle cost analysis should be done. The 12 basic steps for such an analysis are as follows:

1. Define the system requirements and technical performance measures;
2. Specify the system life cycle and identify activities by phase;
3. Develop a cost breakdown structure;
4. Identify input data requirements;
5. Establish costs for each category in the cost breakdown structure;
6. Select a cost model for analysis and evaluation;
7. Develop a cost profile and summary;
8. Identify high-cost contributors and establish cause-and-effect relationships;
9. Conduct a sensitive analysis;
10. Identify priorities for problem resolution;
11. Identify additional alternatives;
12. Evaluate feasible alternatives and select a preferred approach.

2.6 Gas Turbine Background

In the Brayton cycle process, air is compressed in the compressor. The compressed air is mixed with fuel and ignited in the combustor. The combustion increases the temperature, velocity, and volume of the gas flow. This flow is directed through a nozzle over the turbine's blades, spinning the turbine and powering the compressor. Energy is then extracted in the form of shaft power, compressed air and thrust which is used for auxiliary output.

2.6.1 The Gas Turbine Operation – Brayton Cycle Analysis

The air-standard model of a gas turbine power cycle is depicted in the Brayton Cycle. The three main components of a simple gas turbine are the compressor in the front, coupled to a turbine at the end, with a combustion chamber in between. These components are graphically illustrated in Figure 2.6.1.

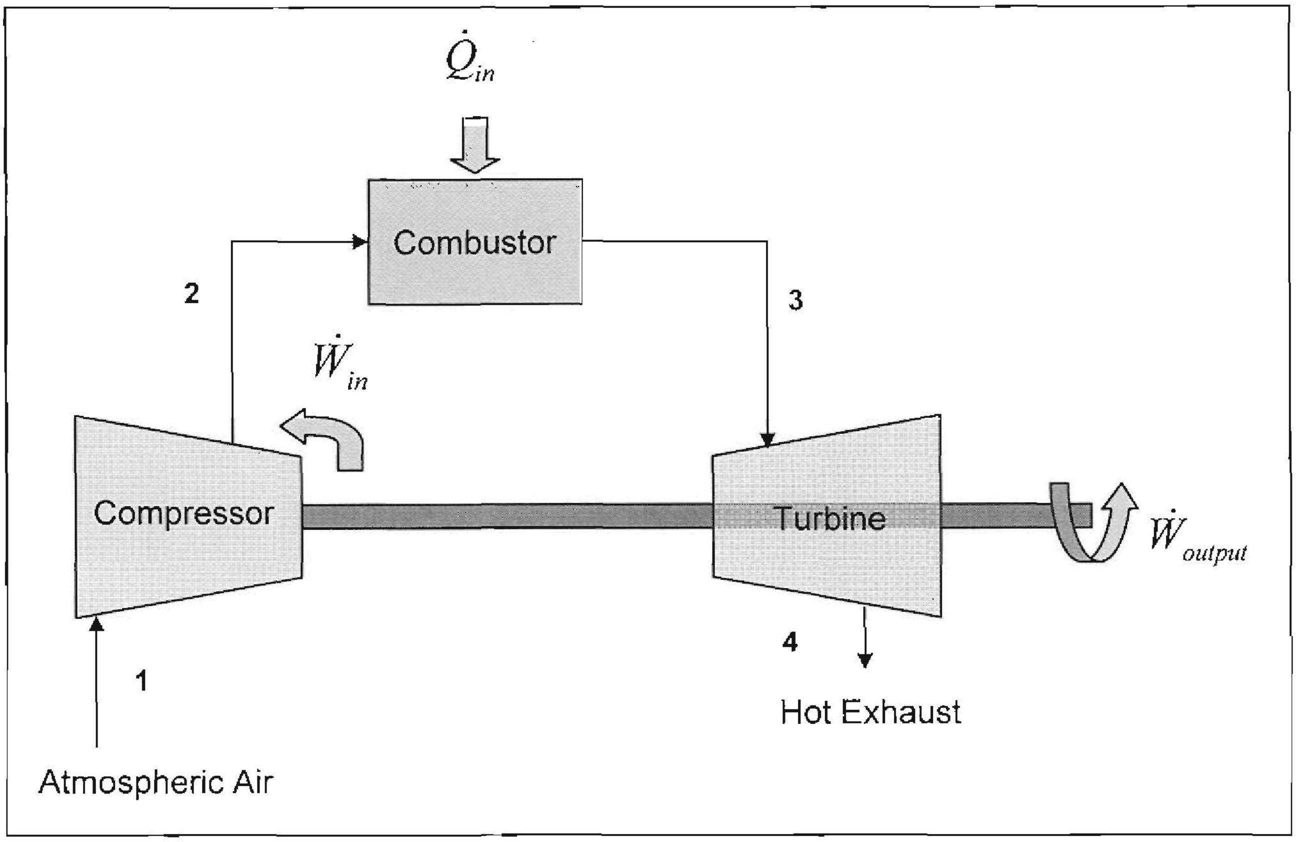


Figure 2.6.1 An Illustration of the Brayton Cycle Concept [5]

Figure 2.5 illustrates the four basic states of the Brayton cycle. At state 1, low-pressure air is drawn into the compressor. This low-pressure air is compressed to a higher pressure at state 2. In the combustor, fuel is added to the compressed air. This mixture is burned in the combustion chamber. The burning mixture generates hot gases that enter the turbine at state 3 and expands to state 4. These four processes of the Brayton cycle can be summarized as follows:

- State 1→ 2: Isentropic compression:

  Low-pressure air is drawn into the compressor (state 1) where it is compressed into a higher pressure (state 2).

- State 2→ 3: Reversible constant pressure heat addition:

  The compressed air is mixed with fuel where it is burnt in the combustion chamber.

- State 3→ 4: Isentropic expansion:

  The hot gasses, resulting from the burnt mixture, enter the turbine (state 3) and expand to state 4.

- State 4 → 1: Reversible constant pressure heat rejection:
  Exhaust and intake in the open cycle.

The overall energy transfer is determined by the thermodynamics. In order to analyze the cycle, all the states need to be evaluated as thoroughly as possible. Air standard models will be used for this purpose because they provide acceptable quantitative results for gas turbine cycles. The following assumptions are made in these models:

- Air is used as the working fluid, treated as an ideal gas throughout the cycle;
- The combustion process is modeled as a constant-pressure heat addition;
- The exhaust is modeled as a constant pressure heat rejection process.

In cold air standard models, it is assumed that the specific heat of air is constant at the lowest temperature in the cycle.

A control volume, containing each component of the cycle shown in Figure 2.6.1 is used to perform the thermodynamic analysis [5].

Step 1: The Compressor [5]

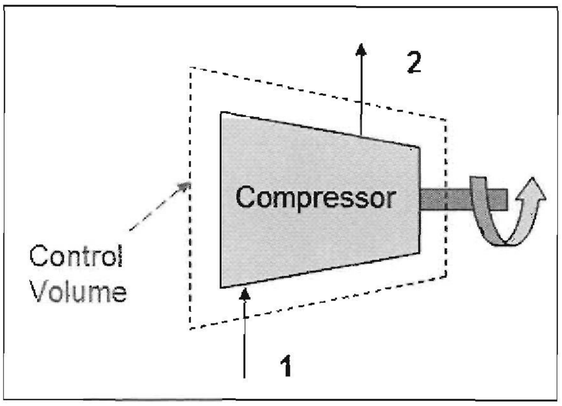


Figure 2.6.2 The Control Volume for the Compressor

The control volume considered for the compressor is shown in Figure 2.6.2. Ideally, there is no heat transfer for the control volume to the surroundings. When neglecting the kinetic and potential energy effects, and under steady state conditions, the first law for this specific control volume can be written as:

$$\dot{H}_{in} - \dot{W}_{in} = \dot{H}_{out} \tag{2.1}$$

If there is one flow into the control volume and one flow out of the control volume, the first law can be rewritten as follows:

$$\dot{m}h_{in} - \dot{m}w_c = \dot{m}h_{out} \tag{2.2}$$

The terms can then be regrouped:

$$-w_c = h_{out} - h_{in} \tag{2.3}$$

This is the general form of the first law for a compressor.

If the fluid stream is assumed to be ideal gases, the enthalpies can be represented in terms of temperature by using the appropriate equation of state, $dh = c_p dT$. If constant specific heats are assumed, enthalpy differences are expressed as temperature differences as follows:

$$-w_c = c_{p,C}\left(T_{C,out} - T_{C,in}\right) \tag{2.4}$$

To obtain a more accurate result, the heat of each fluid should be evaluated at the linear average between its inlet and outlet temperature, $\left(\dfrac{T_{in} + T_{out}}{2}\right)$.

The irreversibilities present in the real process can be modeled by introducing the compressor efficiency:

$$\eta_{comp} = \frac{W_{C,s}}{W_{C,a}} = \frac{h_{out,s} - h_{in}}{h_{out,a} - h_{in}} \tag{2.5}$$

Here the subscript *s* refers to the ideal (isotropic) process while the subscript *a* refers to the actual process. For a perfect gas, the equation above is reduced to:

$$\eta_{comp} = \frac{T_{out,s} - T_{in}}{T_{out,a} - T_{in}} \tag{2.6}$$

Step 2: The Combustor [5]

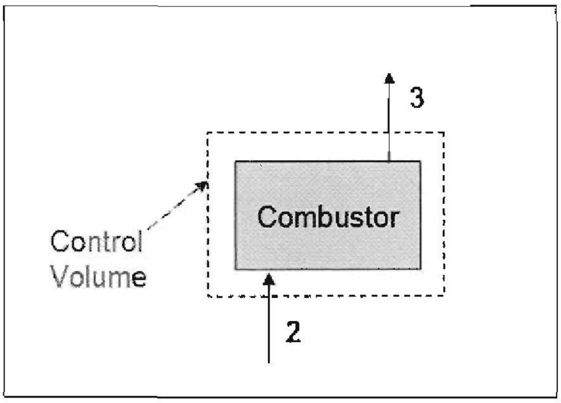


Figure 2.6.3 The Control Volume for the Combustor

For the combustor, the control volume in Figure 2.6.3 is used. Ideally, a work transfer from the control volume to the surroundings exists. Under steady state conditions and by neglecting the effects of the kinetic and potential energy, one can write the first law for this control volume as follows:

$$\dot{H}_{in} + \dot{Q}_{in} = \dot{H}_{out} \tag{2.7}$$

If there is one flow into the control volume and one flow out of the control volume, this first law can be rewritten in a more specific form:

$$\dot{m}h_{in} + \dot{m}q_c = \dot{m}h_{out} \tag{2.8}$$

After rearranging by means of grouping, the terms associated with each stream follows:

$$q_B = h_{out} - h_{in} \tag{2.9}$$

When assuming ideal gases with constant specific heats, enthalpy differences are readily expressed as temperature differences as follows:

$$q_B = C_{p,B}(T_{B,out} - T_{B,in}) \tag{2.10}$$

Again, to increase accuracy, the specific heat of each fluid should be evaluated at the linear average between its inlet and outlet temperatures.

Step 3: The Turbine [5]

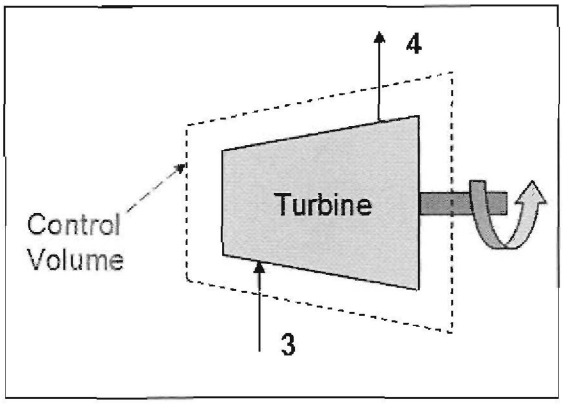


Figure 2.6.4 The Control Volume for the Turbine

The control volume under consideration for the turbine is illustrated in Figure 2.6.4. Again, note that there is no heat transfer from the control volume to its surroundings in ideal condition. When neglecting the kinetic and potential energy effects, and under steady state conditions, the first law for this specific control volume can be written as:

$$\dot{H}_{in} - \dot{W}_{out} = \dot{H}_{out} \tag{2.11}$$

If one flow is considered into the control volume and one flow out of the control volume, the first law can be more specifically written as:

$$\dot{m}h_{in} - \dot{m}w_T = \dot{m}h_{out} \tag{2.12}$$

After the appropriate rearrangements, it follows:

$$-w_T = h_{out} - h_{in} \tag{2.13}$$

When assuming ideal gases with constant specific heats, enthalpy differences are readily expressed as temperature differences as follows:

$$-w_T = C_{p,T}\left(T_{T,out} - T_{T,in}\right) \tag{2.14}$$

As in the previous steps, the specific heat of each fluid should be evaluated at the linear average between it inlet and outlet temperatures to increase the accuracy of the results.

The irreversibilities present in the real process can be modeled by introducing the isentropic efficiency of the turbine:

$$\eta_{TURB} = \frac{W_{C,a}}{W_{C,s}} = \frac{h_{out,a} - h_{in}}{h_{out,s} - h_{in}} \tag{2.15}$$

Again, the subscript *s* refers to the ideal (isotropic) process while the subscript *a* refers to the actual process. For a perfect gas, the equation above is reduced to:

$$\eta_{TURB} = \frac{T_{out,a} - T_{in}}{T_{out,s} - T_{in}} \tag{2.16}$$

2.6.2 Sensor Placements

The required sensor placements to analyze the gas turbine according to the Brayton cycle are as follows:

2.6.2.1 Pressure sensors

- Compressor inlet static pressure (P_1);
- Compressor stage exit stagnation pressure (P_2);
- Combustion chamber pressure (P_3);
- Turbine exit stagnation pressure (P_4);
- Thrust nozzle exit stagnation pressure (P_5).

2.6.2.2 Temperature sensors

- Compressor inlet static temperature (T_1);
- Compressor stage exit stagnation temperature (T_2);
- Turbine stage inlet stagnation temperature (T_3);
- Turbine stage exit stagnation temperature (T_4);
- Thrust nozzle exit stagnation temperature (T_5).

2.6.2.3 Other sensors

- Fuel flow sensor;
- Thrust output;
- Speed sensor (RPM).

The motivation for these sensor locations can be found in [9], the mini-dissertation of Mr. J.S. Oosthuizen who was responsible for the mechanical part of the project.

These are also the sensors equipped in the SR-30 engine used for the MiniLab test facility from Turbine Technologies.

2.6.3 Gas Turbine Safety Precautions

Due to the high rotational speeds and combustion of the turbine, operating a gas turbine can be extremely dangerous, and therefore the necessary safety precautions should always be followed. The following are general safety procedures that must be followed when operating a gas turbine test bench:

- Make sure the operator and spectators are wearing ear protection. Do not stay in the laboratory without wearing ear protection.
- The turbine runs at very high rotational speeds. Never lean to close to the gas turbine while running, even though there is a protective plane. Never open the protective plane while the unit is running.
- If something wrong is noticed at any time, shut of the engine immediately by closing the fuel flow.
- Make sure that nothing is placed in front of the intake or the exhaust exit while the engine is running. These areas should be kept clear at all times while the engine is running.

2.7 Instrumentation

Instrumentation sensors will be used to determine the required parameters of the gas turbine engine. Temperatures, pressures, speed, fuel flow and thrust need to be measured.

2.7.1 Temperature Sensing

A widely used temperature sensor is the thermocouple, a sensor converting thermal potential difference into electric potential difference. This electrical potential difference is generated when any conductor is subjected to a thermal gradient, called the thermoelectric or Seedbeck effect.

A variety of thermocouples are available, usually selected based on the temperature range and sensitivity needed for the application. The two conducting materials to construct the Type-K thermocouple are Nickel-Chromium Alloy and Nickel-Aluminum Alloy. The Type K-thermocouple is the most commonly used general purpose thermocouple. Due to its popularity, it is also inexpensive and available in a wide variety of probes. Type-K thermocouples are available in ranges from -200°C to +1200°C, with a sensitivity of 41µV/°C [6].

2.7.2 Pressure Sensing

Pressure sensors are typically used to generate an electrical signal related to the imposed pressure on the sensor. These sensors are used for monitoring and control in everyday applications.

Various types of pressure sensors exist, varying in technology, design performance, application suitability and cost. The types of pressure sensors can be divided into 5 types [7]:

- Absolute pressure sensor:
  The pressure is measured relative to perfect Vacuum (0 PSI or no pressure), where atmospheric pressure is about 100kPa (14.7 PSI) at sea level.
- Gauge pressure Sensor:
  This sensor can be calibrated to measure the pressure relative to a given atmospheric at a given location.
- Vacuum pressure sensor:
  This sensor can be used to measure a pressure less than the atmospheric pressure at a given location.
- Differential pressure sensor:
  This sensor measures the difference between two or more pressures applied as inputs to the sensing unit.
- Sealed pressure sensor:
  This sensor is equivalent to the gauge sensor, but is pre-calibrated by the manufacturer to measure pressure relative to sea level.

A gauge pressure sensor will be used for this application because the pressure readings are referenced to atmospheric pressure. This sensor can also be used to measure positive and negative output pressures. Negative pressure readings might be obtained when the gas turbine engine chokes.

2.7.3 Thrust Sensing

A strain gauge can be used to measure deformation (strain) of an object. It consists most commonly of an insulating flexible backing that supports a metallic foil pattern. The gauge can then be attached to an object by an adhesive to determine the strain in that object. The strain measured can be tension or compression. The output resistance of the gauge is measured - this resistance increases under tension or decreases under compression.

In order to compensate for temperature variations, a Wheatstone bridge arrangement can be used. This arrangement consists of four strain gauges, two mounted on the one side of the object with the remaining two on the other side [8].

The thrust of the turbine can be measured using strain gauges that are mounted on a cantilevered beam. The gas turbine engine will be mounted on this beam with the strain gauges sensing the elongation and shrinkage of the beam at the fixed end that is configured as a Wheatstone bridge.

2.7.4 Speed Sensing

The speed of the gas turbine engine will be sensed by a hall-effect sensor. This sensor varies its output voltage in response to changes in magnetic field. Therefore, a magnet needs to be mounted onto the compressor blades to generate a changing magnetic field as the engine runs. This changing magnetic field can be sensed and the speed can be determined accordingly.

2.7.5 Fuel Flow Sensing

Ideally, a flow meter can be used to determine the fuel flow into the gas turbine engine. In this system, an alternative option can be used because the fuel pump needs to be driven by a control unit to vary the fuel flow. The pump can be characterized and by capturing the drive signal of the pump the fuel flow rate can be determined accordingly. If the characterization of the fuel pump is properly done, this indirect method of fuel flow sensing should be acceptable. By eliminating the need for a flow meter additional costs can be saved with an acceptable accuracy.

Chapter 3
Preliminary Design

3.1 Introduction

The preliminary design is performed in this chapter. The design is in the form of a functional analysis where the functionality of the complete system is analyzed by doing an analysis of all operational and maintenance functions. Functional units are then defined to actually execute these functions. A resource allocation is used to map all system functions to functional units. This mapping is done in a resource allocation matrix.

First, the functional analysis is performed, consisting of an operational analysis and architecture. The operational analysis is done in a functional flow format. The resource allocation for the functional analysis is done at the end of this section. The system layout, together with the grounding of the system is discussed at the end of this chapter. Here, the physical locations of the functional units are shown.

3.2 Functional Analysis

A functional analysis for the gas turbine measurement system is performed in this section.

First, the operational analysis of the system is performed. This involves all the actions that need to be executed in order to operate and maintain the system. The operational analysis is then broken down into sub-levels, each level contains more detail. The focus of this section is on the *function* and *fit* of the system.

The system architecture follows the operational analysis. The system architecture shows all the functional units needed together with the resulting interfaces between the functional units. The functional units and interfaces are broken down into sub-levels to give information that is more specific. In this section, the focus shifts to the *form* and *fit* of the system.

The system operational flow and system architecture form the functional analysis of the system at operational level. In these two sections, the form and function of the system are defined. Once the operational analysis and system architecture has been finalized, one can relate all the operations derived in the operational analysis to functional units and interfaces in the system architecture. This requirements allocation is done in a table format in section 3.2.5.

3.2.1 System Operational Analysis

The highest level of the operational analysis consists of the actions that need to be taken by the operator and the maintenance personnel to use the system. Thereafter each operation is broken down into sub levels up to the technical level. The detail level is discussed in Chapter 4, the detail design.

The operational flows are shown separately in this section. The complete operational analysis can be found in Appendix B, where all the operations are shown on one page.

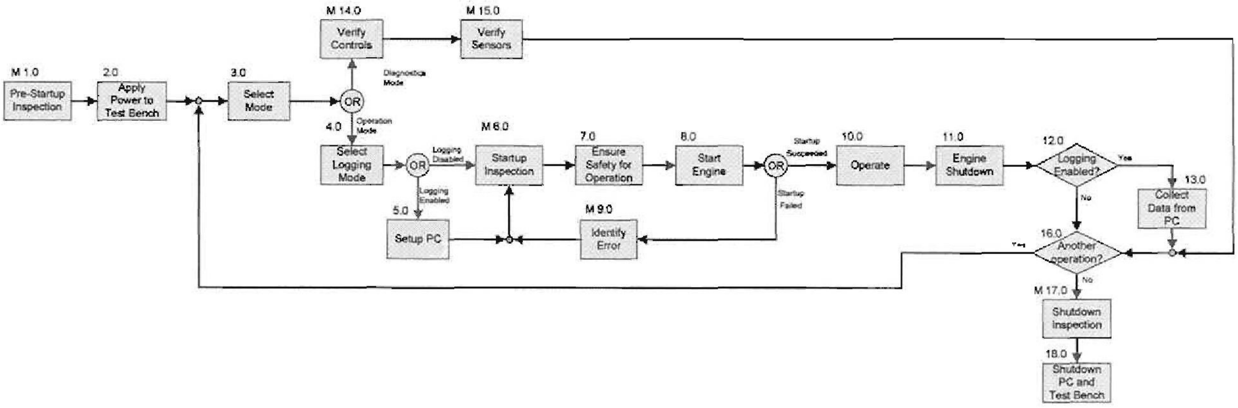


Figure 3.2.1 System Operational Flow (First Level)

Figure 3.2.1 shows the operational flow of the gas turbine measurement system. Each block is numbered as an Operational Function (O/F) or a Maintenance Function (M/F). This notation is followed throughout this section.

Each of the functions depicted in Figure 3.2.1 is broken down into sub-levels as follows:

- ***M/F 1.0 - Pre-Startup Inspection***

The startup inspection needs to be done first. In Figure 3.2.2 the pre-startup Inspection is broken down, after which each of these functions is broken down to level three.

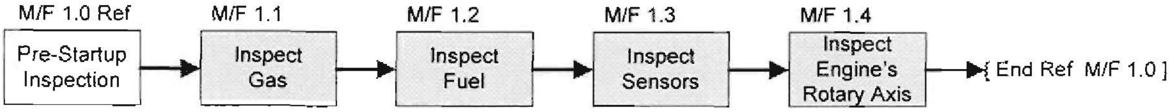


Figure 3.2.2 Pre-Startup Inspection (Second Level – Maintenance Flow)

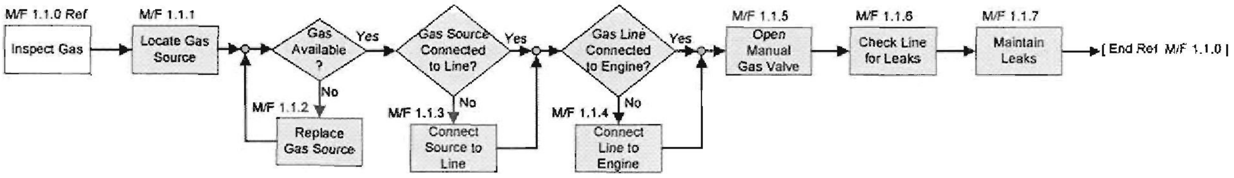


Figure 3.2.3 Gas Inspection Procedure (Third Level – Maintenance Flow)

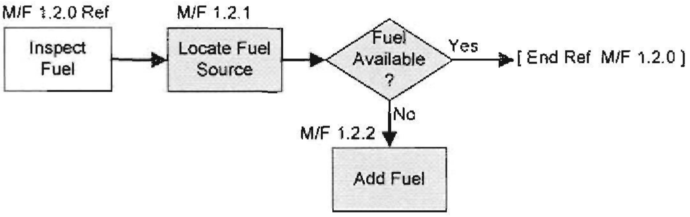


Figure 3.2.4 Fuel Inspection Procedure (Third Level – Maintenance Flow)

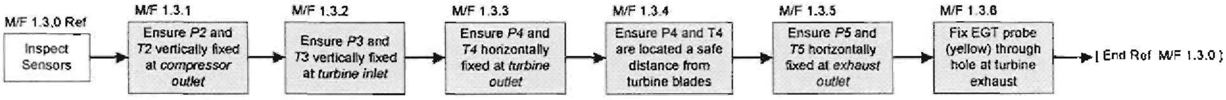


Figure 3.2.5 Sensors Inspection Procedure (Third Level – Maintenance Flow)

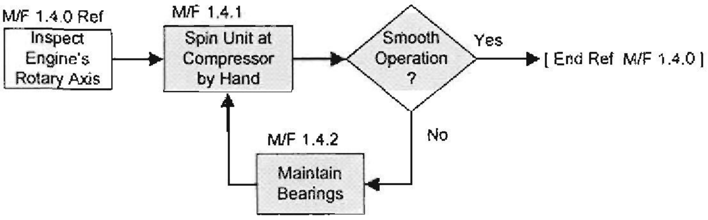


Figure 3.2.6 Engine's Rotary Axis Inspection Procedure (Third Level – Maintenance Flow)

- ***O/F 2.0 - Apply Power to Test Bench***

During this function, the power should be supplied to the system. This is a straight-forward operation. Figure 3.2.7 shows this operation up to level two.

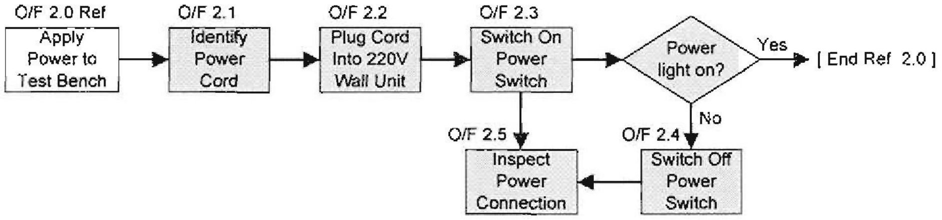


Figure 3.2.7 Procedure to Apply the Power to the Test Bench (Second Level – Operational Flow)

- ***O/F 3.0 - Select Mode***

The system provides an operational mode and a diagnostics mode. In the operational mode, the engine can be started and operated while data is logged. During the diagnostics mode, all the controls and sensors can be verified. Figure 3.2.8 shows how to select the operational mode and diagnostics mode.

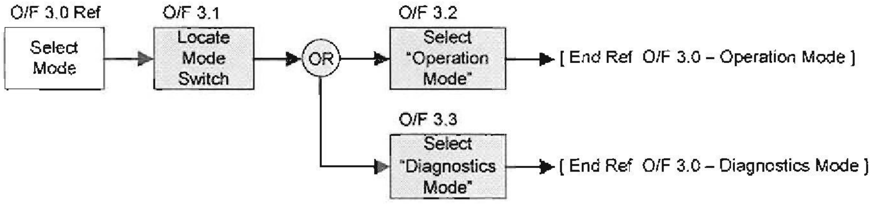


Figure 3.2.8 Mode Selection Procedure (Second Level – Operational Flow)

- ***O/F 4.0 - Enable / Disable Logging***

When this mode is enabled, the data obtained from the sensors will be logged to the PC. No data will be sent to the PC if this mode is disabled. This mode should be disabled if the test bench is used without a PC. Figure 3.2.9 illustrates the procedure to set the logging mode.

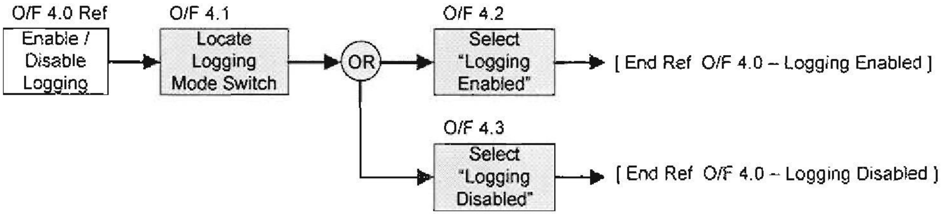


Figure 3.2.9 Procedure to Enable or Disable the Logging Mode (Second Level – Operational Flow)

- ***O/F 5.0 - Setup PC***

The PC should be set up in order to log the data if logging mode is enabled. All the data from the sensors shall be logged and displayed on the PC. The data is also saved in a Microsoft Excel spreadsheet format for future use and analysis. The procedure to set up the PC is shown in Figure 3.2.10.

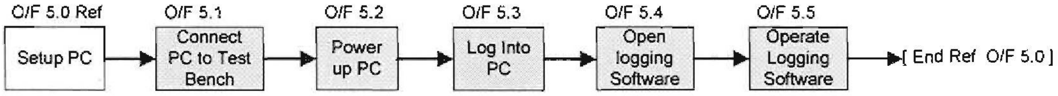


Figure 3.2.10 The PC Setup Procedure (Second Level – Operational Flow)

- ***M/F 6.0 - Startup Inspection***

The startup inspection procedure is executed just before the engine is started. Here the fuel line needs to be primed, if necessary. This ensures that the line is filled with fuel and that there are no air bubbles in the line. If the fuel line is not primed when necessary, the unit might choke or fail to start. Figure 3.2.11 shows the complete startup inspection procedure while the procedure to prime the fuel line is illustrated in Figure 3.2.12.

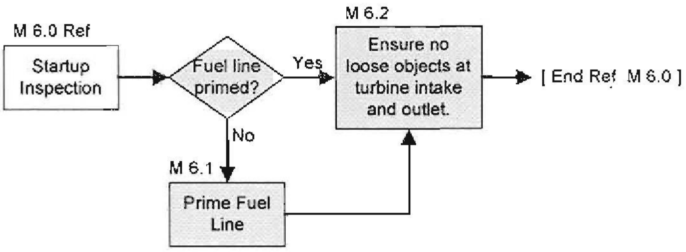


Figure 3.2.11 Startup Inspection Procedure (Second Level – Maintenance Flow)

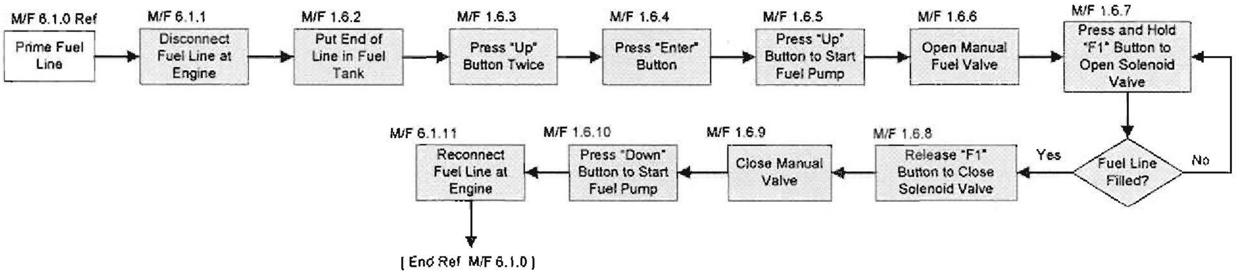


Figure 3.2.12 Procedure to Prime the Fuel Line (Third Level – Maintenance Flow)

- ***O/F 7.0 - Ensure Safety for Operation***

The safety procedures throughout the design process are important. This safety procedure should be executed just before startup as illustrated in Figure 3.2.13.

Ear protection should be fit due to engine running noise. It is important that the safety panel should be closed and locked to keep the operator safe from the high-speed engine. This also prevents obstacles from being sucked into the engine at the intake.

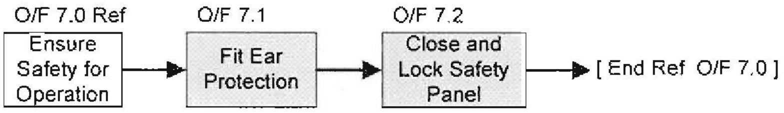


Figure 3.2.13 Procedure to Ensure Safety before Startup (Second Level – Operational Flow)

- ***O/F 8.0 - Start Engine***

Once all the required safety procedures and inspections have been executed, the engine can be started. The procedure to start the engine is shown in Figure 3.2.14.

After the *Start* button has been pressed, the control dial needs to be turned to the maximum and back to the minimum. Only then will the system enter the *Auto Start Procedure* as illustrated in Figure 3.2.15.

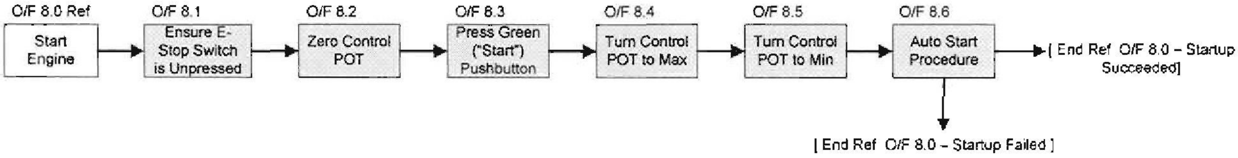


Figure 3.2.14 Procedure to Start the Engine (Second Level – Operational Flow)

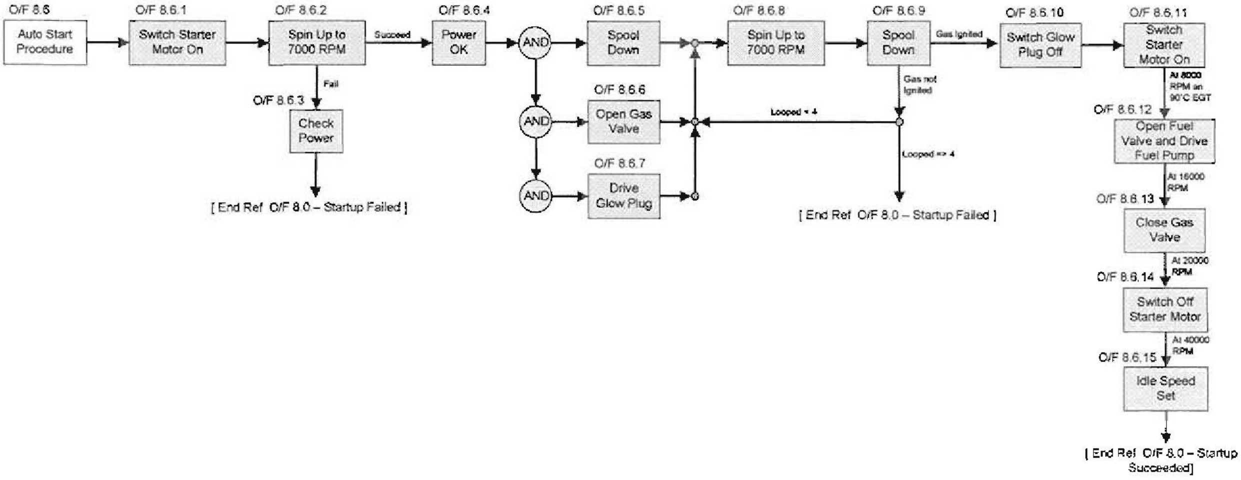


Figure 3.2.15 The Auto Start Procedure (Third Level – Operational Flow)

- ***M/F 9.0 - Identify Error***

If startup fails, the fault should be identified and repaired. Some known issues are illustrated in the flow from Figure 3.2.16, thereafter, each of these issues is broken down to one more level in the following figures.

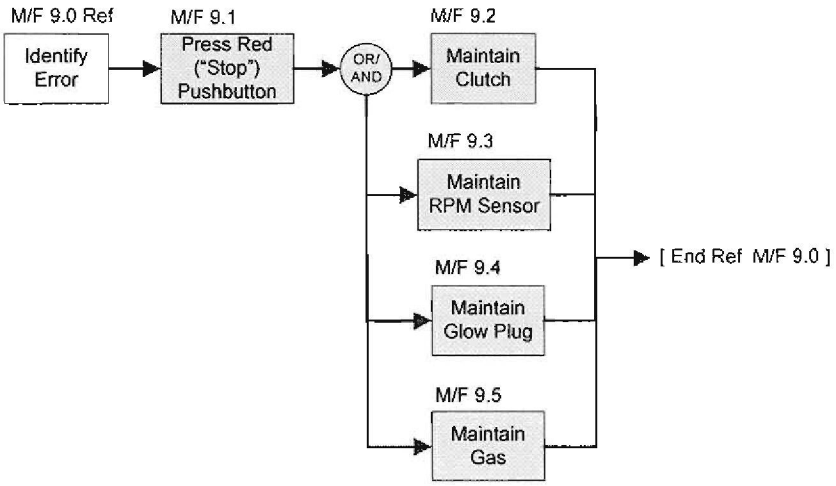


Figure 3.2.16 Error Identification Procedure (Second Level – Maintenance Flow)

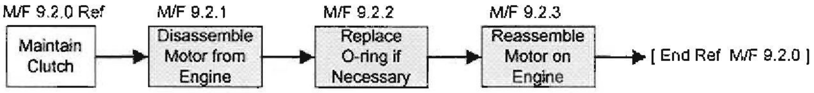


Figure 3.2.17 Clutch Maintenance Procedure (Third Level – Maintenance Flow)

The clutch maintenance procedure should be executed if the starter motor is running but the rotary axis of the compressor is not turning. The O-ring from the clutch of the starter motor should be replaced to get better grip on the compressor axis.

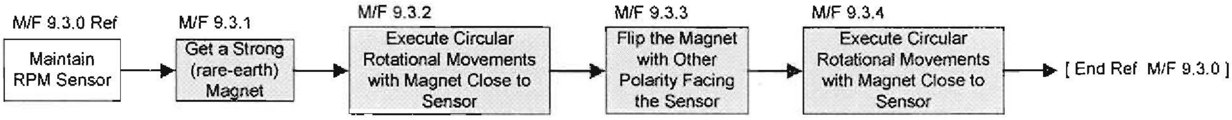


Figure 3.2.18 Speed Sensor Maintenance Procedure (Third Level – Maintenance Flow)

It could happen that the speed sensor is magnetized resulting an incorrect output. To demagnetize this sensor, the procedure in Figure 3.2.18 should be followed.

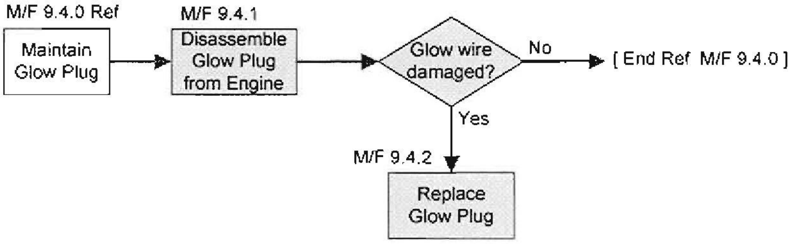


Figure 3.2.19 Glow Plug Maintenance Procedure (Third Level – Maintenance Flow)

If the gas does not ignite, it could be that the glow plug is faulty and needs to be replaced. See Figure 3.2.19.

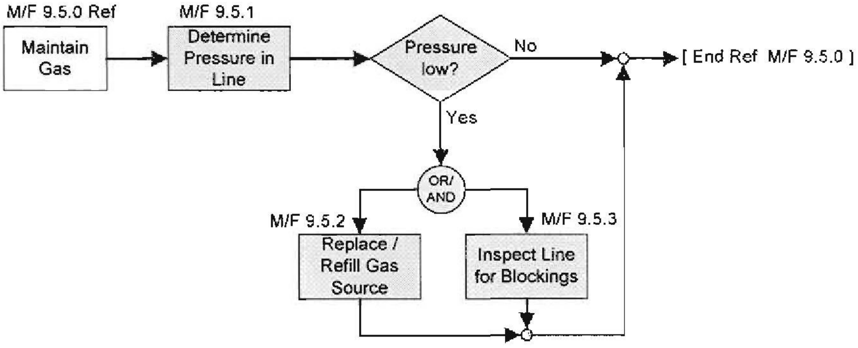


Figure 3.2.20 Gas Maintenance Procedure (Third Level – Maintenance Flow)

If the gas ignites during startup but does not reach an exhaust gas temperature (EGT) of at least 90°C then it could be that the pressure in the gas line is too low. Follow the procedure in Figure 3.2.20 to correct this problem.

- ***O/F 10.0 - Operate***

Once the engine has executed the startup procedure and reaches the idle state (40 000 RPM), the unit can be operated. The operation procedure is shown in Figure 3.2.21.

Each of these functions is broken down to the third level in the following figures.

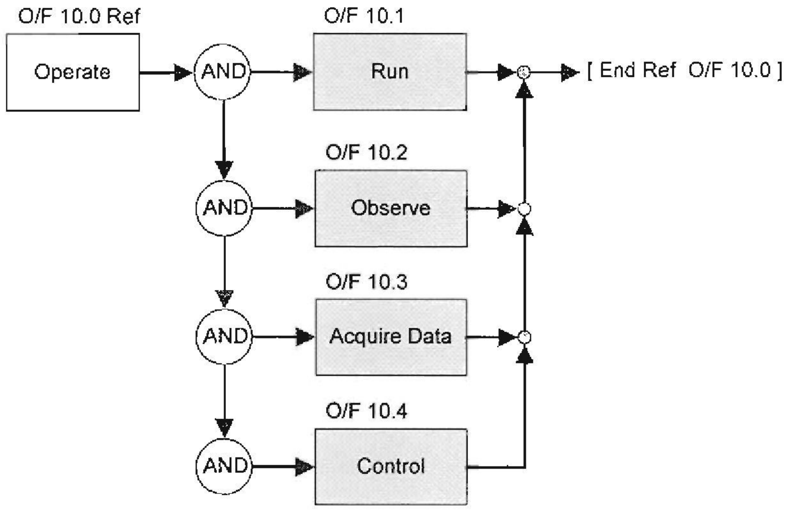


Figure 3.2.21 Operation Procedure (Second Level – Operational Flow)

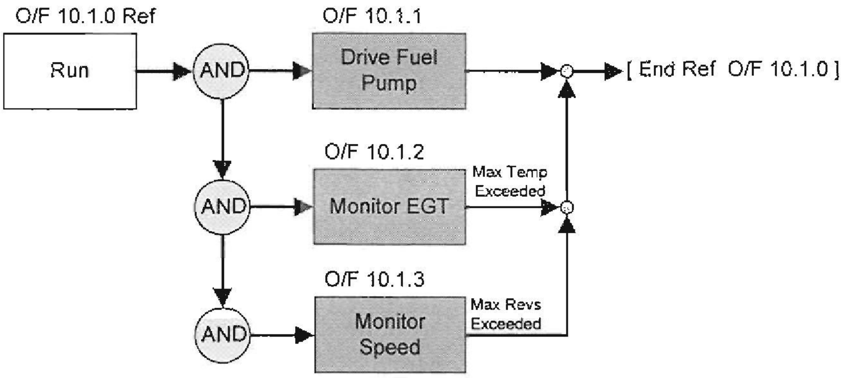


Figure 3.2.22 Run Procedure (Third Level – Operational Flow)

In the run procedure, the safety control unit (SCU) monitors the speed and exhaust gas temperature. If these values exceed the maximum allowable value, the engine will shut down immediately. This unit is also used to drive the fuel pump. The SCU is a buy-in item which is available "off the shelf" at an affordable price.

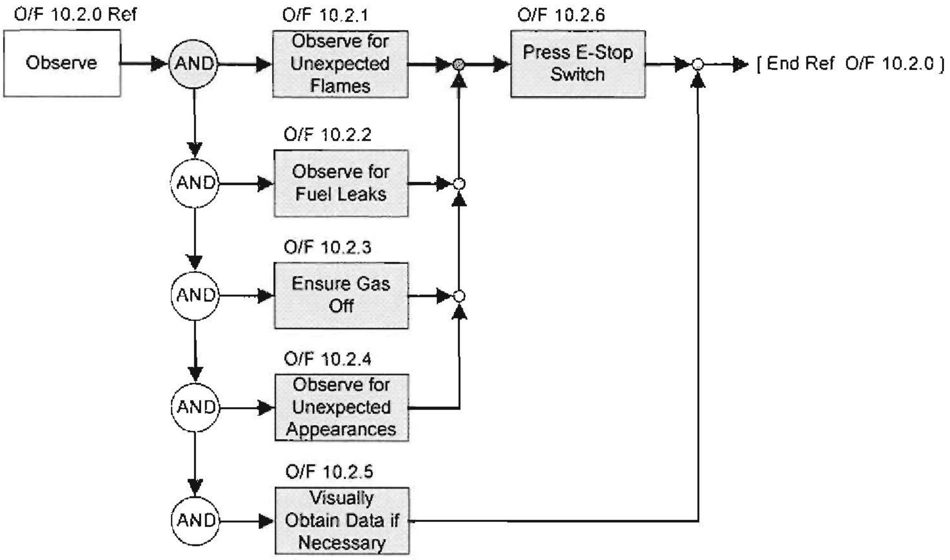


Figure 3.2.23 Observe Procedure (Third Level – Operational Flow)

Although safety precautions and automatic shutdown procedures are in place, observation for faults is critical while the engine is running. If at any time during operation unexpected flames, fuel leaks, or any unwanted appearances are observed, the engine should be shut down immediately. This can be done by pushing the emergency stop lockable switch - the switch should be in the locked state. The engine should also be shut down if the gas appears to be on above speeds of 16 000 RPM. If the gas stays on (for some reason, as it is switched of automatically by the control unit) it could damage the engine.

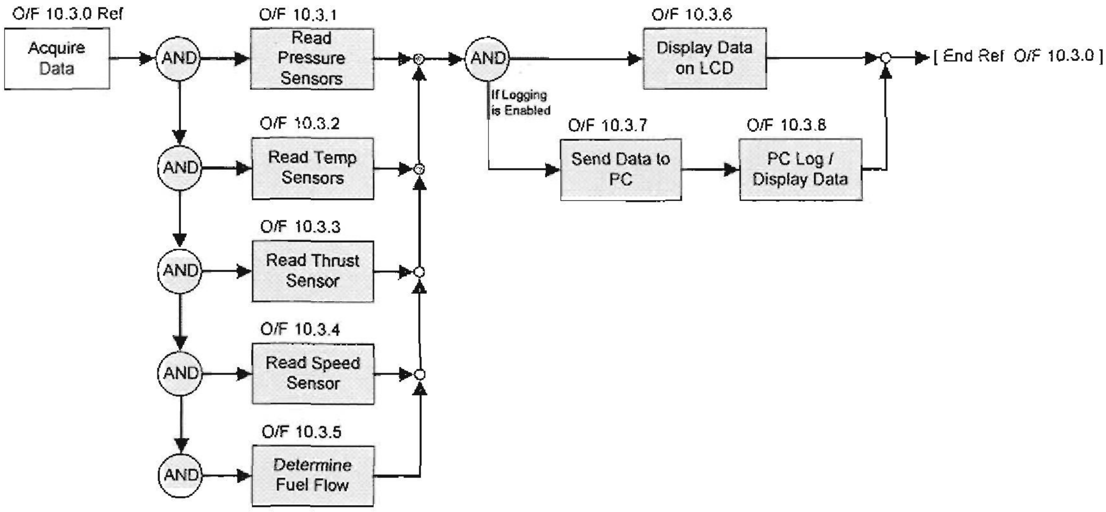


Figure 3.2.24 Procedure to Get and Log the Data (Third Level – Operational Flow)

All the sensors should be read in order to get complete data. Thereafter the data is interpreted and sent to the PC (if logging is enabled) and displayed on the display unit for visual real time display.

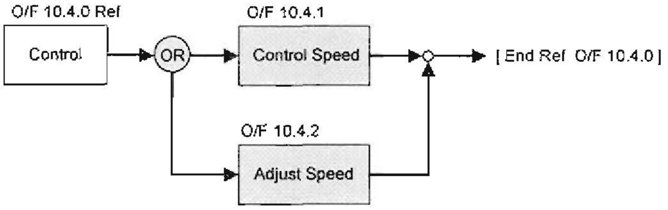


Figure 3.2.25 Control Procedure (Third Level – Operational Flow)

The engine's speed can be controlled via the control dial. This dial can be turned clockwise to increase the speed and counterclockwise to decrease the speed. A single turn dial is used.

- ***O/F 11.0 - Shutdown Engine***

If *O/F 10.0 Operate* is completed the system should be shut down. The shutdown procedure is illustrated in Figure 3.2.26.

Note that the system could also have shut down automatically by the SCU if any critical parameters have been exceeded or if the emergency stop button was pressed in the O/F 10.2.

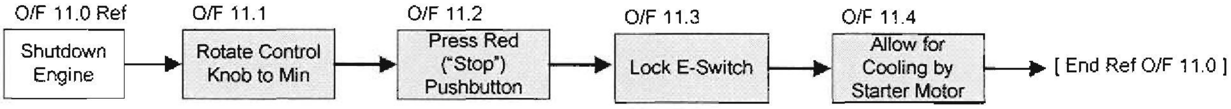


Figure 3.2.26 Shutdown Procedure (Second Level – Operational Flow)

- ***O/F 12.0 - Logging Enabled?***

Determine if the logging is enabled by checking the logging switch as set in O/F 4.0.

- ***O/F 13.0 - Collect Data from PC***

After all the data has been logged, the data can be saved to spreadsheet format by a save button on the GUI. The graphs on the GUI can then be reset by the reset button, to get the GUI ready to collect new data.

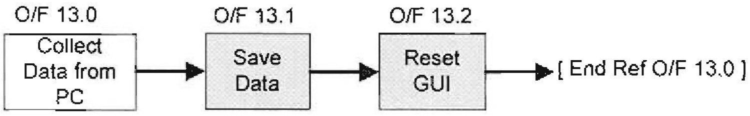


Figure 3.2.27 Data Collection Procedure (Second Level – Operational Flow)

- ***M/F 14.0 - Verify Controls***

When in diagnostics mode, the controls on the control panel can be verified as a maintenance function. This mode, as illustrated in Figure 3.2.28, can simplify fault finding to ensure that all the buttons and controls are working.

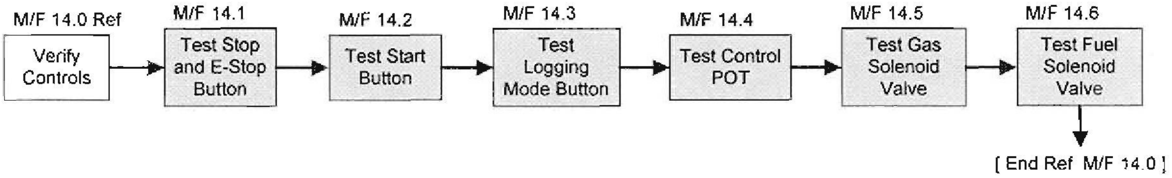


Figure 3.2.28 Procedure to Verify the Controls (Second Level – Maintenance Flow)

- ***M/F 15.0 - Verify Sensors***

After the controls have been tested, the thrust, pressure, and temperature sensors can be verified. The thrust sensor is verified by applying force onto the engine or mounting beam in the x-direction. To verify the temperature and pressure sensors, heat and pressure must be applied to these sensors.

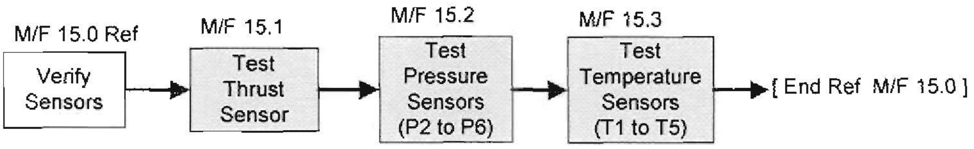


Figure 3.2.29 Procedure to Verify the Sensors (Second Level – Maintenance Flow)

- ***O/F 16.0 - Another Operation?***

If another operation is required the user should go to O/F 3.0, else the user should proceed with the shutdown inspection, M/F 17.0.

- ***M/F 17.0 - Shutdown Inspection***

Once operation is complete and no further operations are required, the shutdown inspection should be done to ensure safety and proper storage for future operations.

After the fuel valve has been closed, the fuel line should also be disconnected from the engine. This is to ensure that the engine doesn't get filled with fuel as this can damage the engine at the next startup. The gas valve should also be closed and the gas source removed to prevent gas leaks.

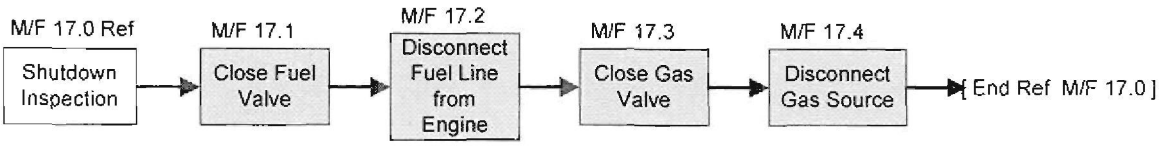


Figure 3.2.30 Shutdown Inspection Procedure (Second Level – Maintenance Flow)

- ***O/F 18.0 - Shutdown PC and Test Bench***

Finally, the PC and test bench should be switched off, and the power to the test bench should be removed. This procedure is shown in Figure 3.2.31.

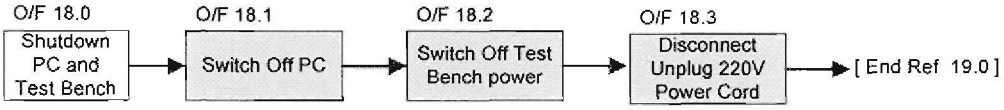


Figure 3.2.31 PC and Test Bench Shutdown Procedure (Second Level – Operational Flow)

This concludes the system operational analysis for this chapter. This operational analysis defines the *form* and *fit* of the system and enables an operator, with the minimum qualifications, to easily use the system. More detail regarding these functions follows in the detail design phase, chapter 4.

3.2.2 System Architecture

The system architecture shows how components fit to form a unified system. The architecture in Figure 3.2.32 illustrates, in block-diagram format, all the physical components needed to execute the functions of the operational flow with their resulting interfaces (I/F). The functional units (F/U) are then broken down into separate architectures down to a technical level. The required functional units are discussed in detail in chapter 4.

Given the basic system architecture in Figure 3.2.32, each of these functional units is explained and broken down in the following text. The resulting interfaces with a general description can be found at the end of this section in Table 3.1. The complete architecture is also shown in Appendix B.

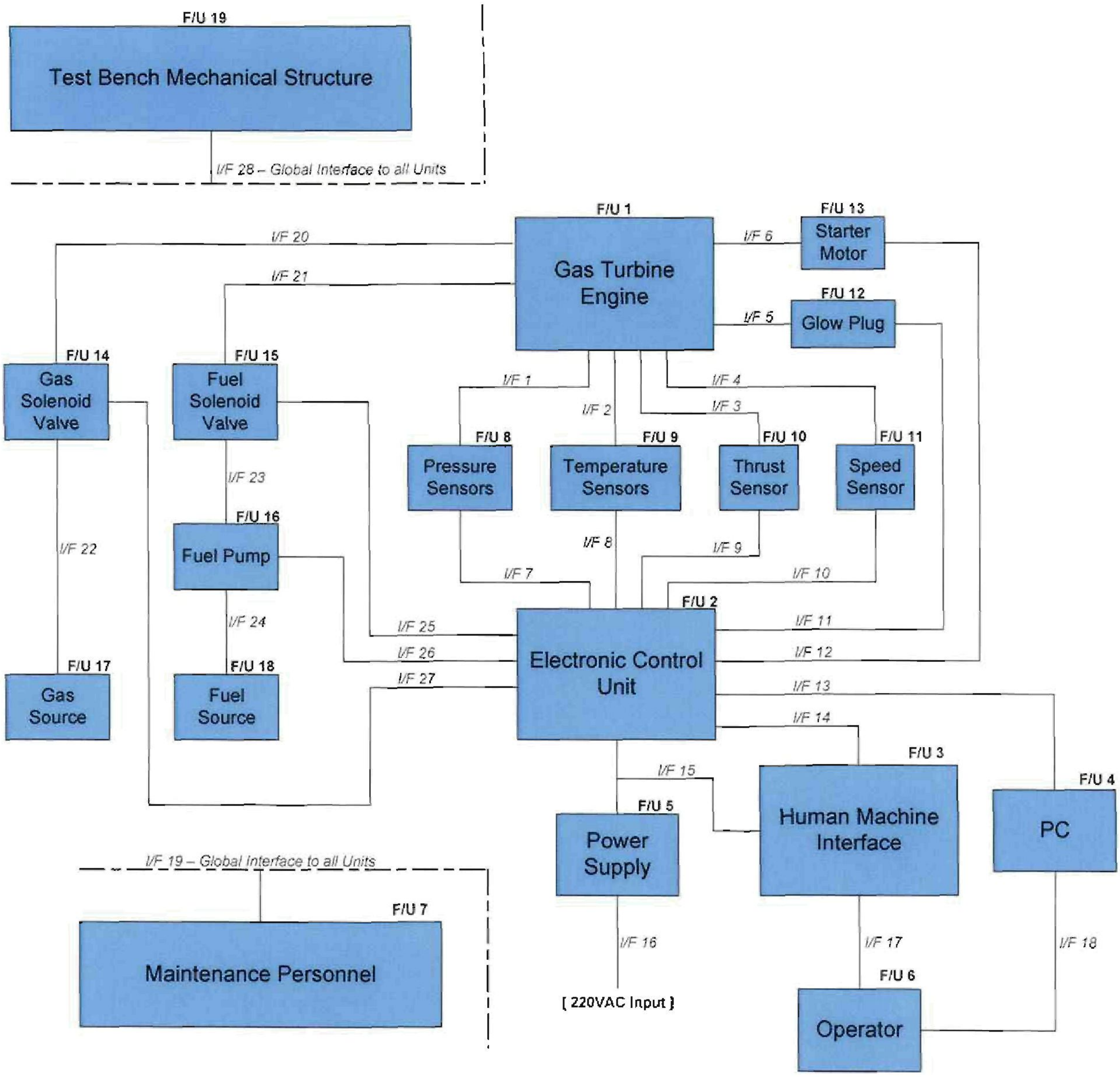


Figure 3.2.32 Gas Turbine Measurement System Architecture (Level 1)

- ***F/U 1 - Gas Turbine Engine***

The gas turbine engine forms the basis for the system. This engine is a buy-in unit, which is modified by the manufacturer to incorporate the temperature and pressure sensors. A more detailed architecture of the gas turbine engine is shown in Figure 3.2.33.

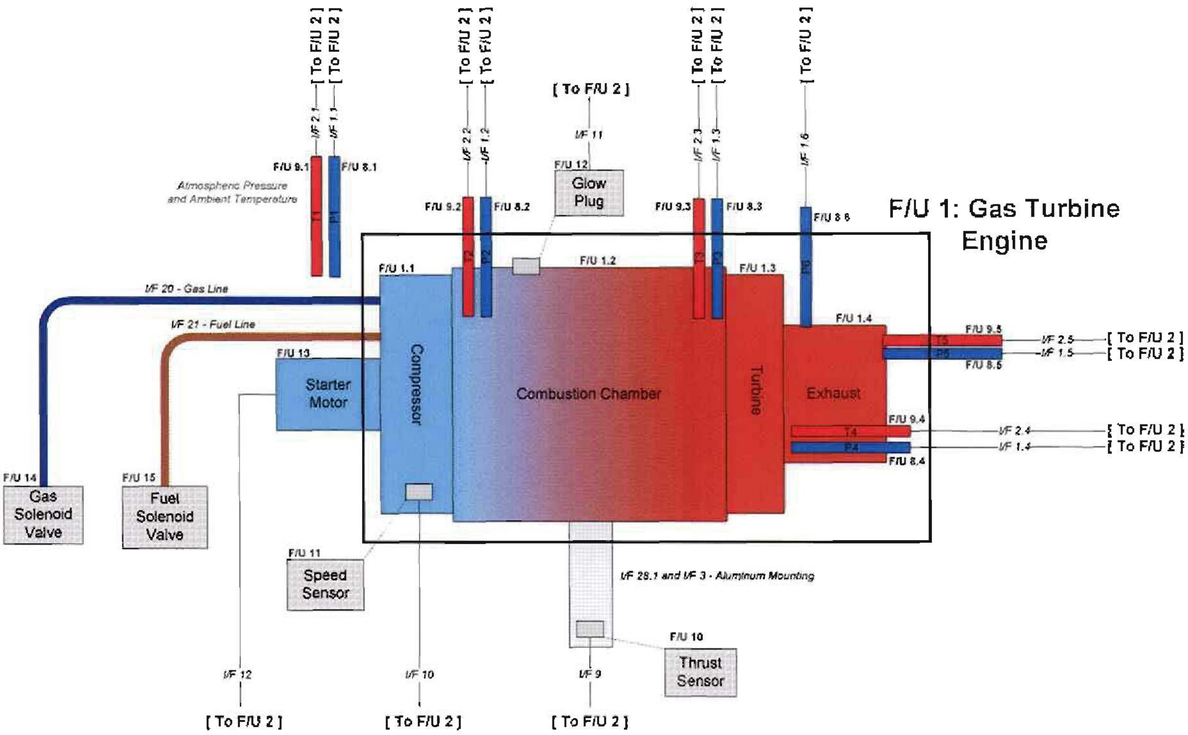


Figure 3.2.33 The Architecture and Interfaces of the Gas Turbine Engine (Second Level)

The engine consists of a compressor in the front, followed by the combustion chamber, turbine and exhaust. The color scheme shows the temperature distribution in the engine under operating conditions.

The pressure and temperature sensors (F/U 8 and F/U 9) are mounted at appropriate places as discussed in section 2.6.2. P6 is also added to determine the static turbine exit stagnation pressure.

The glow plug (F/U 12) is mounted on the engine in the front of the combustion chamber. The glow plug is used to ignite the gas entering the turbine via the gas line (see *I/F 20*). After the gas has ignited, fuel is added (via *I/F 21*) and the burning gas mixture ignites the fuel. Thereafter the gas line is closed to enable the engine to run only on fuel. The fuel and gas lines are controlled by solenoid valves (F/U14 and F/U 15).

The starter motor (F/U 13) is used to "blow" the gas and burning fuel through the engine at the early stages of the startup procedure. Thereafter the burning fuel takes over and the gas is switched off. The starter motor is also switched off and disconnected from the axial shaft of the engine via a clutch mechanism (*I/F 6*).

The speed sensor (F/U 11) is mounted on the outside of the compressor. This is a linear hall-effect sensor, sensing the rotations of the compressor blade via a permanent magnet mounted inside the compressor blades. The speed is sensed at the front of the turbine because this is a cool area, preventing the sensor from getting to hot.

The engine is mounted on an aluminum shaft onto the test bench. A thrust sensor (F/U 10) is mounted on this shaft. The thrust sensor consists of strain gauges. This measured strain gives the thrust output of the engine.

- ***F/U 2 - Electronic Control Unit***

The electronic control unit (ECU) is used to control the turbine while reading all the data from the sensors. The data is processed and sent to the PC and control panel for real-time data display. The broken down structure of the electronic control unit is shown in Figure 3.2.34.

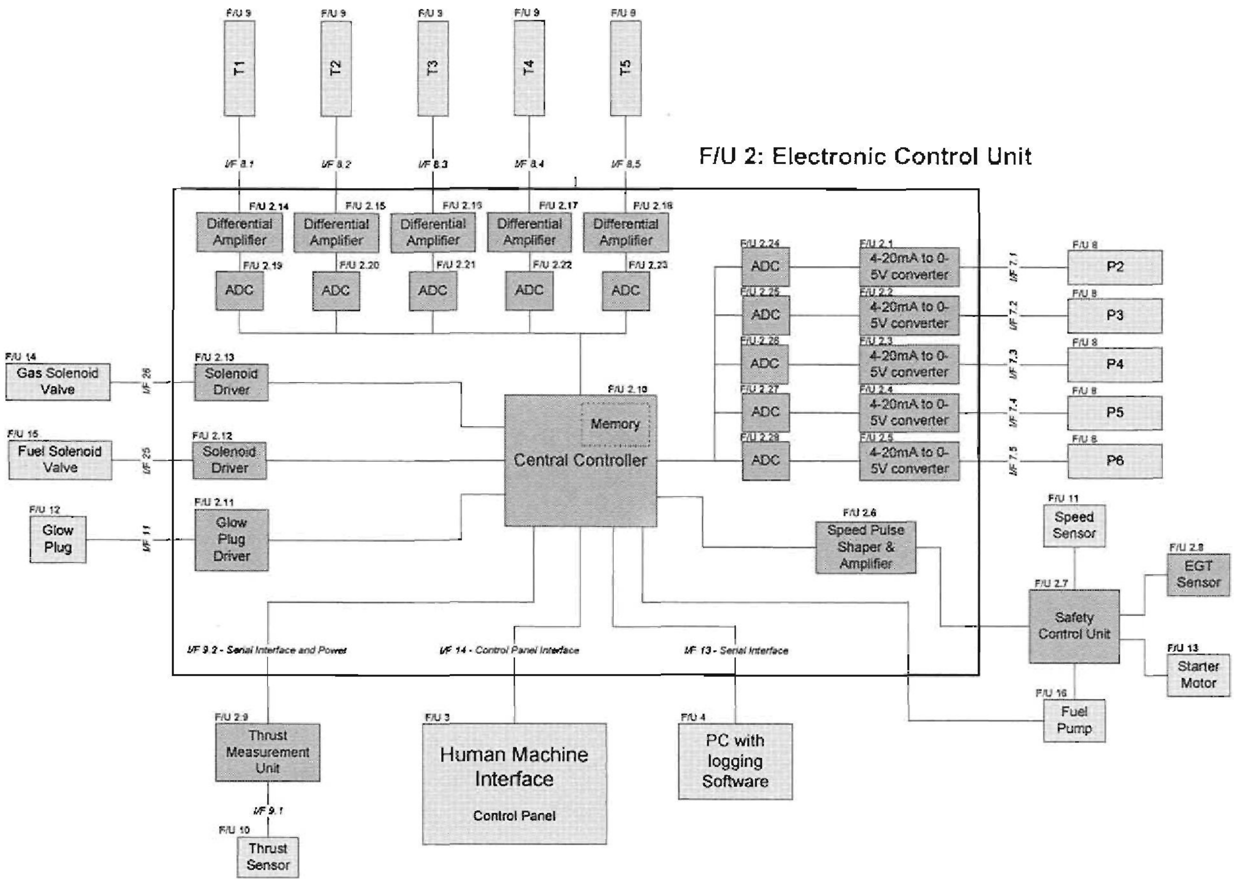


Figure 3.2.34 The Architecture and Interfaces of the Electronic Control Unit (Second Level)

The solenoids for the gas and fuel are switched with relays while the glow plug needs to be driven with a pulse width modulated (PWM) signal. The duty cycle of this pulse determines the glow intensity.

Thermocouples will be used for temperature sensors. The analog output signal is amplified and converted to a digital signal before analyzed by the central controller.

The pressure sensors have 4-20mA outputs. These outputs need to be converted to proportional voltage, and converted to digital signals. This enables the central controller to interpret these signals.

In order to enhance the safety of the system, a safety control unit (SCU) shall be used. This is an affordable buy item, optimized to control the turbine within the safety limitations. This unit monitors the speed (F/U 11) and exhaust gas temperature (F/U 2.8) in order to control the fuel pump (F/U 16). Shutdown mode shall be entered if the predefined maximum speed or temperatures are exceeded.

The PC will be connected via the serial port to the electronic control unit. All the data will be sent to the PC for logging and visual interpretation. The human machine interface (HMI - F/U 3), consisting of a control panel, is also connected to the electronic control unit in order to operate and control the system.

The thrust sensor is very sensitive with respect to external interference. Therefore, a separate measurement unit (F/U 2.9) will be used which can be mounted as close as possible to the strain gauge sensors. The data can then be sent via the serial interface (*I/F 9.2*) to the electronic control unit. This unit is broken down to a lower level in Figure 3.2.35.

F/U 2.9: Strain Gauge Measurement Unit

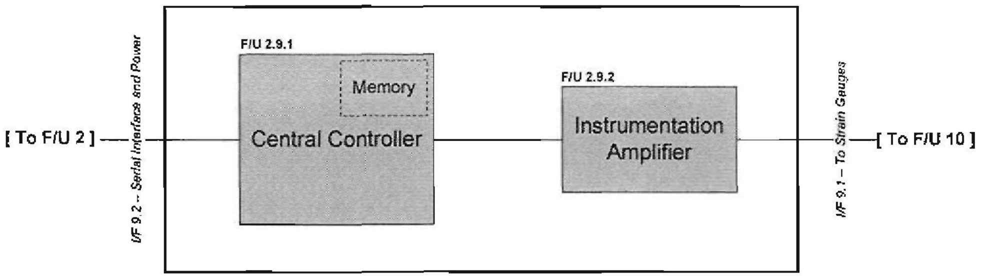


Figure 3.2.35 The Architecture of the Strain Gauge Measurement Unit (Third Level)

- ***F/U 3 – Human Machine Interface***

The human machine interface (HMI) is used by the operator to operate the measurement system. This interface consists of settable buttons, controls, and visual indication. The second level architecture of this control panel is shown in Figure 3.2.36.

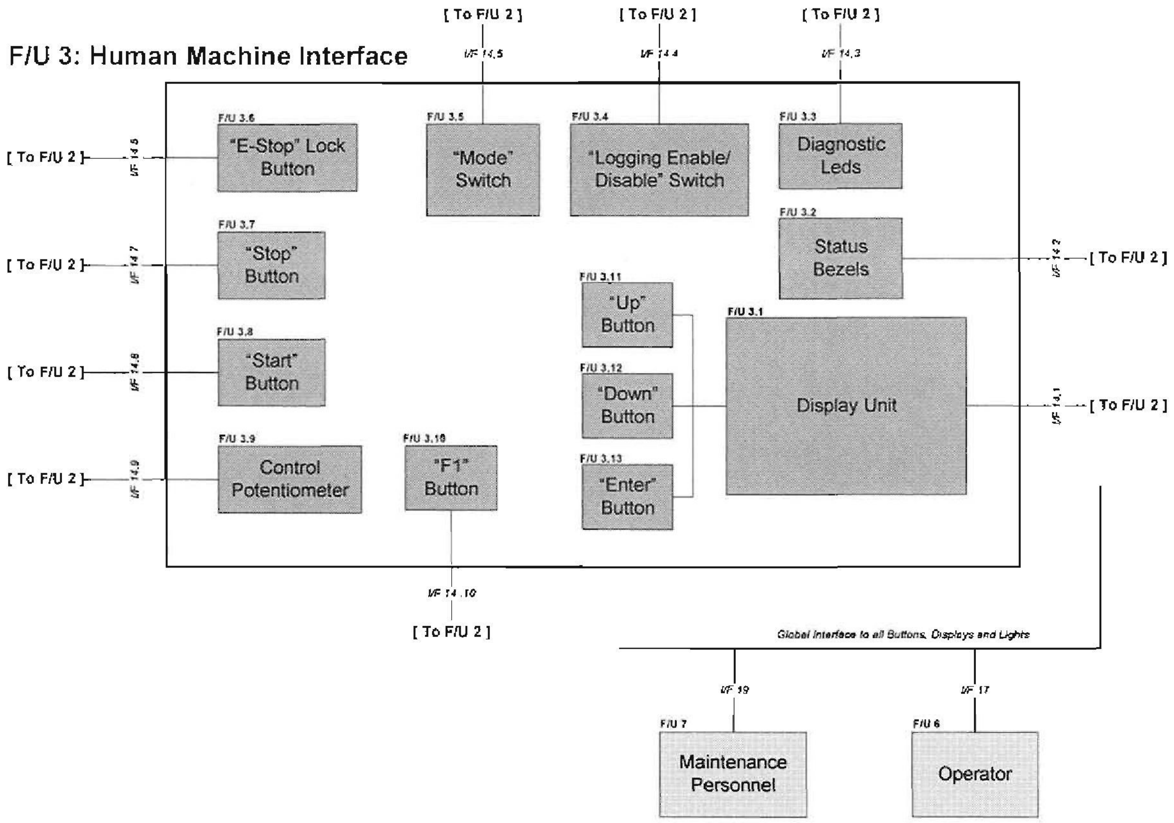


Figure 3.2.36 The Architecture of the Human Machine Interface (Second Level)

The display unit (F/U 3.1) is a separate unit consisting of three liquid crystal displays (LCD's). This unit communicates with a serial interface to the electronic control unit. The display unit is broken down one more level in Figure 3.2.37.

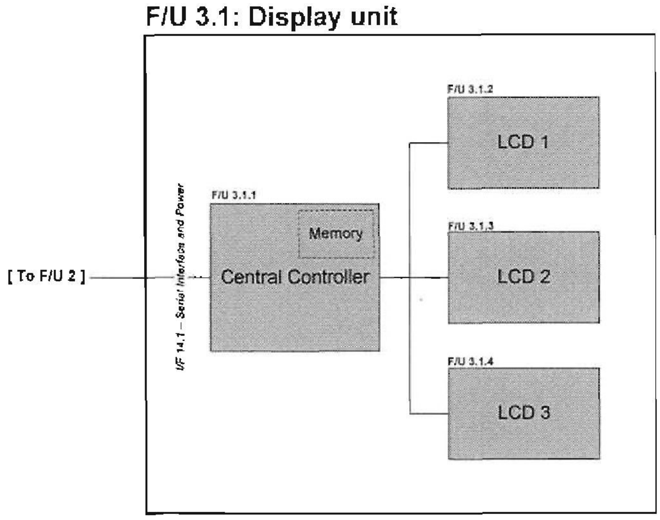


Figure 3.2.37 The Architecture of the Display Unit (Third Level)

- ***F/U 4 - PC***

The PC is used to log and display the data. The PC software captures and analyzes the data. Thereafter the data can be displayed in real time graph format, while the data can also be saved for future references and analysis.

- ***F/U 5 - Power Supply Unit (PSU)***

The power supply unit is used to convert the 220Vac input from the mains, to the required output voltages. The third level breakdown of the PSU architecture is shown in Figure 3.2.38.

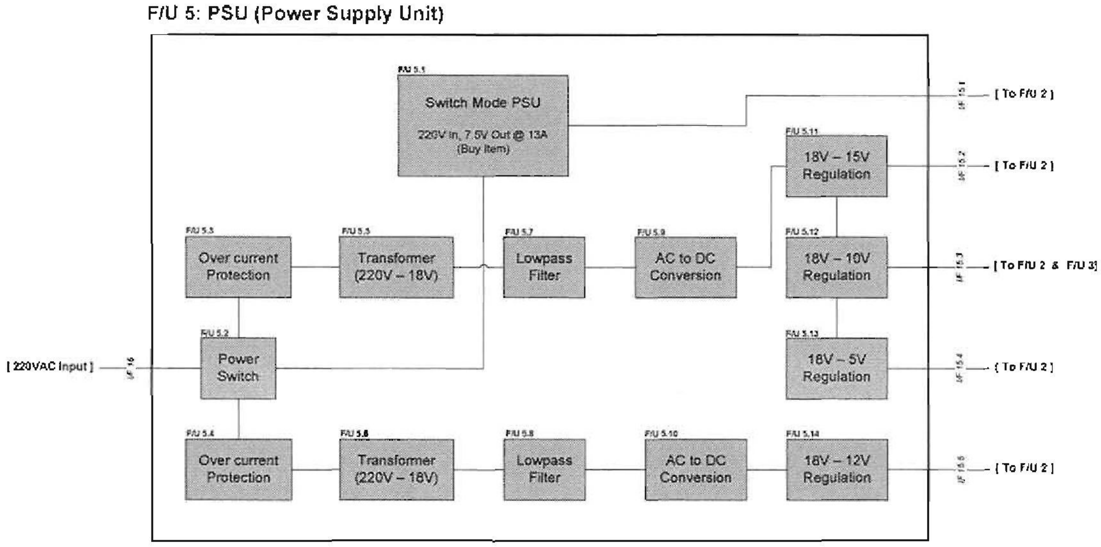


Figure 3.2.38 The Architecture of the PSU (Third Level)

Two transformers are used for two isolated power lines. One shall be used to drive the noisy, medium power drivers while the remaining line shall be used for the sensitive, low power drivers. The high power drivers shall be driven by a separate switch mode PSU, which can deliver the required current for the starter motor, and glow plug.

- ***F/U 6 and F/U 7 - Operator and Maintenance Personnel***

The operator requires training to operate the system and use the system to its full functionality. Only the control panel and PC need to be operated by the operator. In this case, the operator will most often be the lecturer or the students themselves.

The maintenance personnel require a more detailed level of training and should understand the technical detail of the system. All the functional units in Figure 3.2.32 need to be maintained and checked periodically to maintain the system. The maintenance personnel will most commonly be the lecturer or technical staff.

- ***F/U 8 to F/U 15***

These functional units are discussed under F/U 1, the gas turbine engine.

- ***F/U 16 – Fuel Pump***

The fuel pump is used to drive and control the fuel flow to the gas turbine engine (see Figure 3.2.34). A PWM signal is used to drive the pump from the SCU, while the drive signal is also captured by the Electronic Control Unit to determine the fuel flow.

- ***F/U 17 and F/U 18 - Gas and Fuel Source***

A butane/propane gas bottle is used to supply gas to the gas turbine engine. This bottle can easily be disconnected and replaced, if empty, buy a new bottle.

The fuel source consists of the fuel tank. In this case, the fuel consists of a mixture with 95% paraffin and 5% turbine oil. The oil is used to lubricate the bearings as the fuel line splits in two when entering the turbine. One line lubricates the bearings while the remaining line is used to drive the gas turbine engine. In the fuel tank, the fuel is pumped through a filter at the end of the line. This filter ensures that no impurities can enter the engine that will result in unstable operation and damage.

3.2.3 Interface Descriptions

The interface descriptions for the system architecture are shown in Table 3.1.

Table 3.1 General Interface Descriptions for the System Architecture Shown in Figure 3.2.32

	I/F Type				
I/F no:	Electric	Electronic	Mechanical	User	Description
1			x		The mounting of the Pressure Sensors on the Engine
2			x		The mounting of the Temperature Sensors on the Engine
3			x		The mounting of the Thrust Sensor to determine the Engine's thrust
4			x		The mounting of the Speed Sensor on the Engine
5			x		The Glow Plug mounting on the Engine
6			x		The Starter Motor mounting on the Engine
7		x			The output signal from the Pressure Sensors to the Electronic Control Unit
8		x			The signal from the Temperature Sensors to the Electronic Control Unit
9		x			The output signal from the Thrust Sensor to the Electronic Control Unit
10		x			The output signal from the Speed Sensor to the Electronic Control Unit
11		x			The power signal generated from the Electronic Control Unit to drive the Glow Plug
12		x			The power signal generated from the Electronic Control Unit to drive the Starter Motor
13		x			The communication between the PC and the Electronic Control Unit
14		x			The I/O and communication between the Control Panel and Electronic Control Unit and Control Panel
15		x			The power supplied from the Power Supply to the Electronic Control Unit
16	x				The main input power to the Power Supply (220VAC)
17				x	The interface between the User and the Control Panel
18				x	The interface between the User and the PC
19				x	The interface between the Maintenance Personnel and all the system's Functional Units
20			x		The Gas line connecting the Gas Solenoid Valve to the Engine
21			x		The Fuel line connecting the Fuel Solenoid Valve to the Engine
22			x		The Gas line connecting the Gas Solenoid Valve to the Gas Source
23			x		The Fuel line connecting the Fuel Solenoid Valve to the Fuel Pump
24			x		The Fuel line connecting the Fuel Pump to the Fuel Source
25			x		The input power signal from the Electronic Control Unit to drive the Fuel Solenoid Valve
26			x		The input power signal from the Electronic Control Unit to drive the Fuel Pump
27			x		The input power signal from the Electronic Control Unit to drive the Gas Solenoid Valve
28			x		The interface between the Test Bench Mechanical Structure and the mounting of all the system's Functional Units onto this structure.

3.2.4 Software / Firmware Architecture

The architecture for the firmware of the hardware modules (Microcontrollers), together with the software architecture for the PC, is shown in Figure 3.2.39.

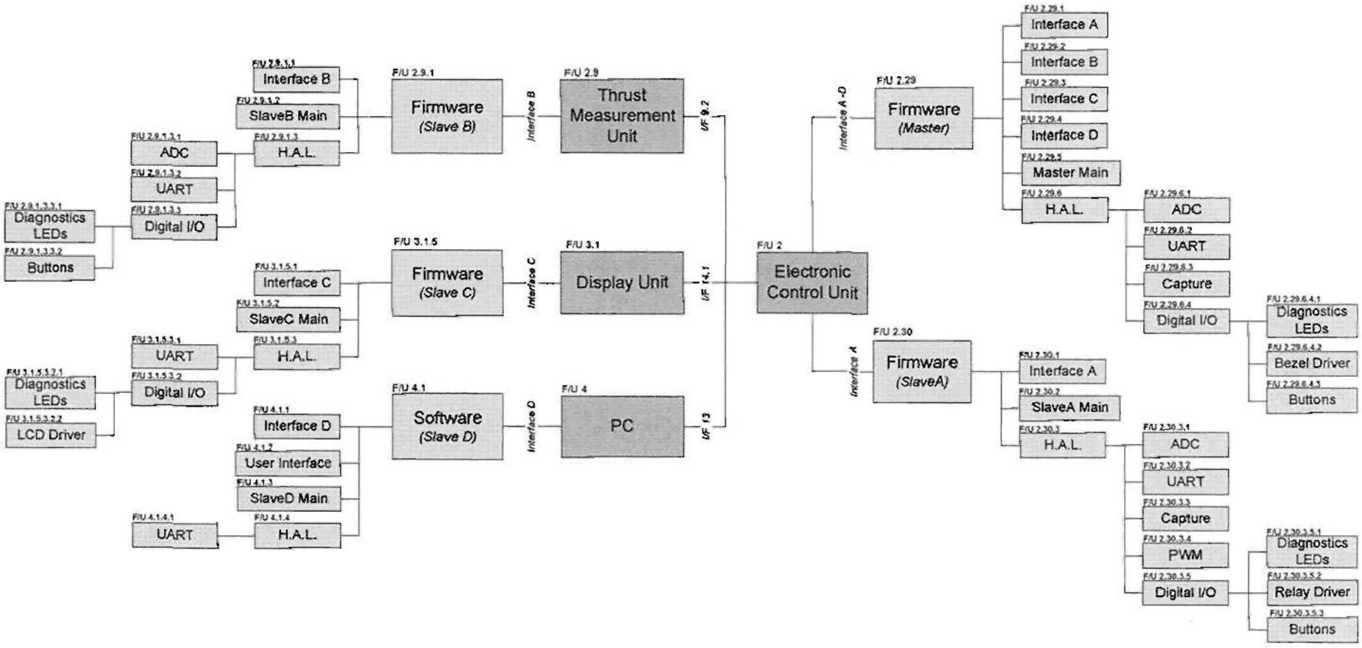


Figure 3.2.39 The Firmware and Software Architecture for the Hardware Modules

In the above illustration, all the functional units containing software or firmware are broken down. As shown, the master unit (F/U 2.29) controls the data flow between the slave units, therefore an interface from the master to each slave unit exists. Interfaces A-D consists of serial communication interfaces. More detail and further breakdowns of the firmware and software design can be found in the following chapter.

3.2.5 Resource Allocation

Table 3.2 The Resource Allocation for the System Analysis

		F/U 1	F/U 2	F/U 3	F/U 4	F/U 5	F/U 6	F/U 7	F/U 8	F/U 9	F/U 10	F/U 11	F/U 12	F/U 13	F/U 14	F/U 15	F/U 16	F/U 17	F/U 18	F/U 19
M/F1.0	M/F 1.1	x					x	x							x			x		
	M/F 1.2						x	x											x	
	M/F 1.3	x					x	x	x	x										
	M/F 1.4	x					x	x												
O/F 2.0	O/F 2.1					x	x	x												x
	O/F 2.2					x	x	x												x
	O/F 2.3					x	x	x												x
	O/F 2.4					x	x	x												x
	O/F 2.5					x	x	x												x
O/F 3.0	O/F 3.1			x			x	x												
	O/F 3.2			x			x	x												
	O/F 3.3			x			x	x												
O/F 4.0	O/F 4.1			x			x	x												
	O/F 4.2			x			x	x												
	O/F 4.3			x			x	x												
O/F 5.0	O/F 5.1		x		x		x	x												x
	O/F 5.2				x		x	x												
	O/F 5.3				x		x	x												
	O/F 5.4				x		x	x												
	O/F 5.5				x		x	x												
M/F 6.0	M/F 6.1	x		x			x	x											x	
	M/F 6.2	x					x	x												x
O/F 7.0	O/F 7.1						x	x												
	O/F 7.2						x	x												x
O/F 8.0	O/F 8.1			x			x	x												
	O/F 8.2			x			x	x												
	O/F 8.3			x			x	x												
	O/F 8.4			x			x	x												
	O/F 8.5			x			x	x												
	O/F 8.6		x																	
M/F 9.0	M/F 9.1			x			x	x												
	M/F 9.2	x					x	x												
	M/F 9.3						x	x				x								
	M/F 9.4						x	x					x							
	M/F 9.5						x	x							x			x		

		F/U 1	F/U 2	F/U 3	F/U 4	F/U 5	F/U 6	F/U 7	F/U 8	F/U 9	F/U 10	F/U 11	F/U 12	F/U 13	F/U 14	F/U 15	F/U 16	F/U 17	F/U 18	F/U 19
O/F 10.0	O/F 10.1		X																	
	O/F 10.2	X		X			X	X							X	X	X		X	
	O/F 10.3		X	X	X				X	X	X	X								
	O/F 10.4		X				X	X												
O/F 11.0	O/F 11.1			X			X	X												
	O/F 11.2			X			X	X												
	O/F 11.3			X			X	X												
	O/F 11.4		X											X						
O/F 13.0	O/F 13.1				X		X													
	O/F 13.2				X		X													
M/F 14.0	M/F 14.1			X			X	X												
	M/F 14.2			X			X	X												
	M/F 14.3			X			X	X												
	M/F 14.4			X			X	X												
	M/F 14.5			X			X	X							X					
	M/F 14.6			X			X	X								X				
M/F 15.0	M/F 15.1			X			X	X			X									
	M/F 15.2			X			X	X	X											
	M/F 15.3			X			X	X		X										
M/F 17.0	M/F 17.1						X	X											X	
	M/F 17.2	X					X	X												
	M/F 17.3						X	X										X		
	M/F 17.4						X	X										X		
O/F 18.0	O/F 18.1				X		X	X												
	O/F 18.2				X		X	X												X
	O/F 18.3				X		X	X												

The resource allocation, as shown in the table above, maps the functions from the functional flow to the functional units in the system architecture. This ensures that the system design fulfills the required functional capability requirements of the system. The functions are shown on the rows - broken down one level - while the functional units from the system architecture are shown on the columns.

3.3 "Design for" Criteria for this Gas Turbine System

3.3.1 Design for EMC

The following criteria were addressed in the design of the measurement sub-system.

3.3.1.1 Split the system into critical and non-critical sections:

- Susceptible circuitry include the sensors and conditioning circuitry;
- A common ground point was selected at a low impedance ground point;

3.3.1.2 Component selection:

- Linear power supplies were used to supply analogue circuits;
- Slew-rate RC filter limiting was applied to high slew-rate digital circuits;
- Low voltage / low current communication was used;
- RF decoupling was used on all components, and RC and LC filters were used on power supplies;
- Resistive and / or capacitive filtering techniques were used at the sensor inputs;
- Differential sensing was used on all analogue circuits.

3.3.1.3 PCB layout:

- Proper signal returns were implemented to ensure that no sensitive lines crossed noisy lines;
- Digital interface paths were kept away from analogue circuits and ground planes were used throughout;
- Ground inductance was minimized by using one or more ground planes with central grounding on low-frequency analogue circuitry;
- High current enclosed loops were minimized in switch-mode PSU design;

- All surface areas of high Δv/Δt areas were minimized to reduce capacitive coupling;
- No floating conductor areas are present on the PCB's;
- Short tracks and cables were used where possible;
- Filters were placed close to IC's and no sensitive components were placed close to high-current or high-voltage ground plane edges (to reduce line current coupling).

3.3.1.4 Cables:

- Signal cables are screened and do not run parallel to power cables;
- Cables do not run close to noisy ground or radiating structures;
- Resonant lengths were not an issue since high-frequency filtering was done and cable-lengths were too short for resonance;
- Cable screens were properly terminated to casings and connectors;

3.3.1.5 System Ground Layout:

- The ground system was designed and enforced at the product definition stage;
- A ground system was used as a return current path instead of a 0V reference – see the ground layout of the system below;
- Common ground impedances were avoided and low-noise / "quiet" grounds were created for all sensitive circuitry;
- A "clean" ground area was provided for the decoupling of all interfaces;

The ground layout of the system is of significant importance to ensure the success of a stable measurement system. This is the first and main consideration when designing for EMC.

Figure 3.3.1 shows where all the functional units, as defined in the functional architecture, are mounted together with their ground connections.

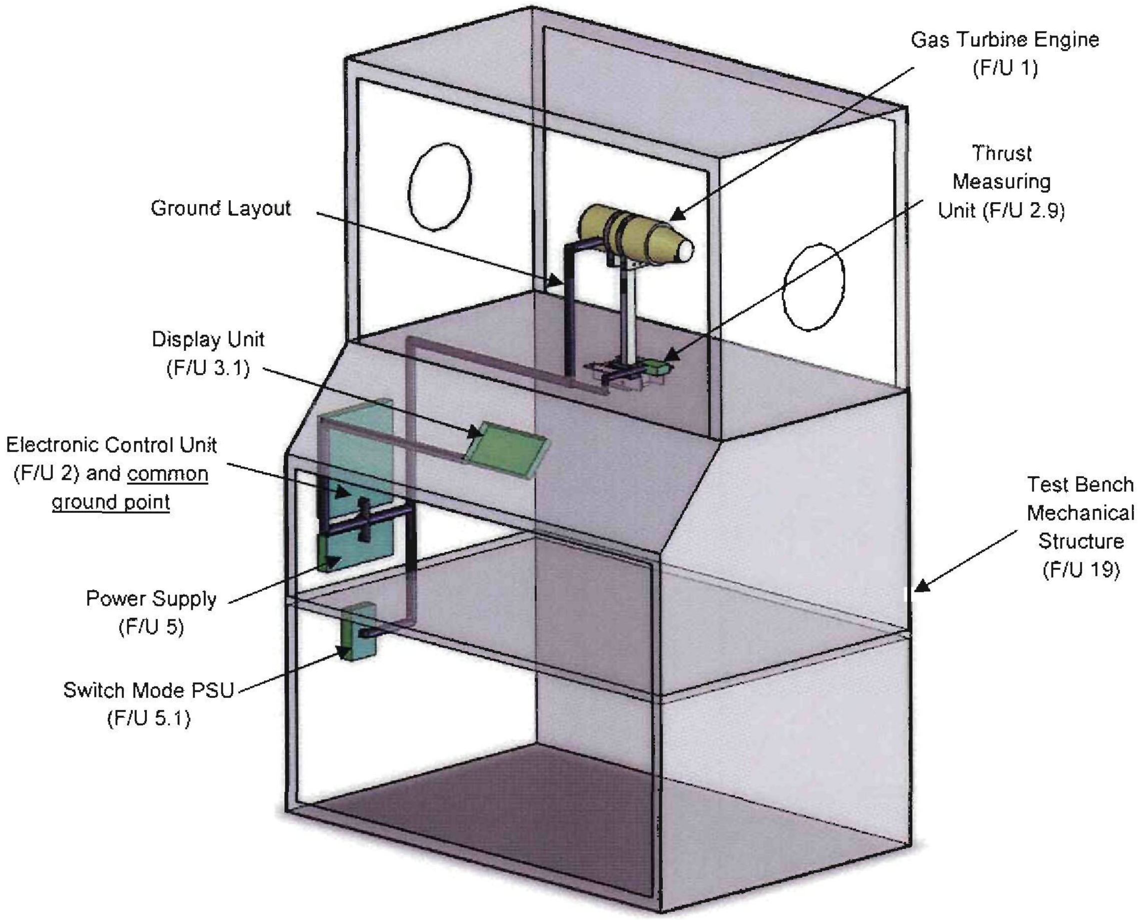


Figure 3.3.1 The Test Bench Ground Layout for the Measurement

The mechanical structure of the test bench is grounded at one point to prevent ground loops. This common point is at the star point of the electronic control unit (F/U 2). Ground is also connected to the casing of the gas turbine engine to drive the glow plug, but is this grounding isolated through a relay. The relay is open when measurements are taken and is this relay only closed when the glow plug is on.

The display unit (F/U 3.1) and the power supply (F/U 5) are the noise generating units, and are therefore mounted as far as possible from the measurement circuitry. This minimizes the noise impact on the measuring circuits. The switch mode PSU (F/U 5.1) is mounted in the bottom of the cabinet to limit the electromagnetic interference (EMI) caused by this unit.

The thrust measuring unit (F/U 2.9) is mounted next to the strain gauges at the bottom of the cantilever beam. This increases the accuracy and stability of the thrust measurement and limits the effects of EMI.

3.3.1.6 Filters:

- The input filter was designed to filter common-mode noise by using capacitors and a common-mode choke;
- A PI filter was used at the main power supply, with a good ground return;
- Isolation was provided between the noisy circuitry and the sensitive circuitry in the form of linear regulation and galvanic isolation.

3.3.1.7 Shielding

- Shielding was required for the thrust sensor circuit in the form of a mild steel casing;
- A shielded cable was used to carry signals from the conditioning circuitry of the thrust sensor to the main board;
- Proper connections were used throughout to ensure shielding effectiveness.

3.3.2 Design for Usability

The following anthropometric considerations were made (under the control of the electronic engineer on this project):

- The height of an average operator was considered with the placement of displays so as to provide an optimum viewing angle;
- Highly visible lights were used to indicate safe / unsafe conditions;

During the functional analysis, specific care was taken to do the following:

- User interfaces were identified and designed to promote usability;
- All user functions are contained in the functional analysis and were used to simplify the required operator actions.

3.3.3 Design for Manufacturability

This was not a major consideration during this development, but specific care was taken to do the following:

- Commonly available components were used to implement the modules of the system;
- Modules were designed in such a way that, should components become obsolete, the functions are clear and may be implemented on new technology;
- Proper manufacturing and design data are provided with the system.

3.3.4 Design for Safety

- Hazardous areas are defined as locations next to the turbine engine itself since the engine may disintegrate and throw pieces of blade etc in all directions;
- Possible causes of hazards include noise, projectiles, and gas explosion that may cause physical harm;
- Hazard effects are (i) permanent damage to hearing or hearing loss and (ii) physical harm in terms of penetration into the body of an operator or spectator resulting from projectiles;
- Hazards are classified as (i) temporary or permanent hearing loss and (ii) injury or death;
- The probability of hazard occurrence is (i) common with noise, and (ii) less common in the case of disintegration of the turbine engine or explosion of gas cylinders;
- Actions that should be taken to eliminate or minimize the hazards include (i) safety procedures as defined in the functional analysis, (ii) a strong physical structure with protective shielding, and (iii) an emergency cut-out.

3.3.5 Design for Maintainability

3.3.5.1 Hardware

- Commonly available components were used as far as possible;
- Effective components were used from a globally known trusted suppliers;
- Widely available CAD tools for design and PCB layout were used – OrCAD®;

3.3.5.2 Software and firmware

- Code was designed to be portable:
    - A consistent style was used to make the code portable to other compilers;
    - An abstraction level was created (by virtue of using functional analysis) by deriving code from higher-level functional analyses.
- All code is readable:
    - A functional design document was created by virtue of using a functional analysis and state-diagrams;
    - Documented introductory comments that provides information of the file and its contents are used throughout;
    - Descriptive comments before every function and procedure were used;
    - Code lines were commented as often as possible;
    - Descriptive names for variables and functions were used;
- Code construction:
    - User interfaces were implemented from the conceptual design through the functional interfaces and functions;
    - Structures were kept in separate modules;
- Code is traceable:
    - A documented design methodology was used (this document included);
    - Well known compilers and CAD tools were used;
    - Each section of the source code is linked to the functional analysis of the system;
    - File names were given that are unique in the context;

3.3.6 Design for Affordability

The 12 basic steps for affordability were followed:

- System requirements and technical performance measures were defined;

- The system life cycle and identify activities by phase were specified;
- A cost breakdown structure was done;
- Input data requirements were identified;
- Costs for each category in the cost breakdown structure were identified – very simplistically as this is not a commercial product;
- A cost model for analysis and evaluation was selected – once off development with little variable cost;
- A cost profile and summary was developed (see Appendix A);
- High-cost contributors were identified as the turbine engine, instrumentation, and labor costs;
- A sensitivity analysis was done and critical items were identified (make vs. buy);
- Priorities for problem resolution were identified very simplistically. Once-off costs were kept to a minimum and labor costs (since it is subsidized) were less important;
- Alternatives were identified and only non-commercial sensors were developed. Most sensors were buy-in items;
- Feasible alternatives were used, for example to develop the thrust sensor instead of buying an expensive load-cell.

3.4 Conclusion

In this chapter the preliminary design was performed. This includes a detailed functional analysis, where the functionality of the system is defined, together with the physical layout and functional units needed. A resource allocation is done together with the placement of the functional units in the ground layout.

The functional analysis from this chapter (see section3.2) will also be used as the support documentation for this system. Therefore, maintenance functions and operational functions are separated in the operational flow to clarify the operations needed to run and maintain the system. The operational analysis and system architecture can be found fully integrated in A3 format in Appendix B. Interface descriptions will also be needed during maintenance together with resource allocations (in order to do fault finding).

In this chapter, the basis for the detail design is set i.e. the *fit*, *form* and *function* of the system is now defined. In the detail design, the design and implementation of the functional units as shown in Figure 3.3.1 is discussed.

Chapter 4
Detail Design

4.1 Introduction

This chapter describes the detail design of the system. The design and implementation of each functional unit that was described in the preliminary design, is discussed in this chapter.

This chapter is done in extensive detail since the system must be maintained in the future by personnel who may not have the prior background that is required to perform maintenance without this knowledge.

The chapter starts with an overview of the implemented Experimental Development Model (XDM). Thereafter the instrumentation is discussed together with its interfaces to electronic circuitry. The Engineering Development Model (EDM) is discussed in detail. This discussion includes the hardware and firmware design for the EDM, together with the software design for the data logging program. All software and firmware designs are illustrated in state diagrams.

4.2 Experimental Development Model (XDM)

The experimental development model was first designed in order to get a prototype model running as soon as possible in order to minimize technical risk. Therefore, this model was roughly built on veroboard as shown in Figure 4.2.1 to demonstrate functional capability and not final form.

Figure 4.2.1 Experimental Development Model

This model consists of three MCUs, each performing the following functions:

- MCU 1
    - Control communication;
    - Read 5 x thermocouple inputs (analog) via amplifiers;
    - Read button inputs;
    - Drive diagnostic LED's;
    - Drive 2 x LCD's for display purposes;
    - Drive 2 x PWM outputs for glow plug and fuel pump;
    - Read thrust sensor via instrumentation amplifier.

- MCU 2
    - Read 5 x analog inputs for pressure sensors;
    - Drive output relays for solenoids;
    - Drive diagnostic LED's.

- MCU 3
    - Read RPM sensor through external interrupt pin;
    - Drive diagnostic LED's.

4.2.1 XDM Shortfalls

Certain shortfalls were identified during the development of the XDM. These are discussed briefly in this sub-section.

1. All of these functions could be integrated into one MCU with the necessary hardware but there were not enough I/O pins on the MCU to incorporate all of these functions. In addition, due to the high rotational speeds of the gas turbine engine, too much processing time would be used to determine the speed via one external interrupt. Therefore, the speed sensor was implemented on a separate MCU. Although a different MCU could have been selected, the support tools and learning curve for a new processor were restricting. The code was developed in such a way that a next generation product can be developed when time allows in the future.

2. In the XDM design, all of the modules were implemented on one board and mounted at one location. Due to the location of the strain gauge placements on the cantilever bar, a long wire was needed to connect the strain gauges to the electronic measuring circuitry where the signal is amplified and read by the MCU. A fair amount of noise is coupled into this long wire, disturbing the signal from the strain gauges (this signal is in the μV range).

3. This XDM works together with the safety control unit (SCU) that controls the gas turbine engine within its safety region. The SCU that was bought in uses an RF remote control to operate the unit. This RF remote control generates a significant amount of noise into the system that resulted in erratic measurements. The LCD's also generate noise that influenced the measurements from sensitive strain gauge sensors.

These issues were all addressed in the in the next development model, the Engineering Development Model (EDM). This model is discussed in detail later in this chapter.

4.3 Instrumentation Sensors

This section describes all the sensors used for the gas turbine measurement system. It is important that the correct sensors are chosen to achieve the optimal results during measurements. Also see section 2.7 for more detail regarding the instrumentation.

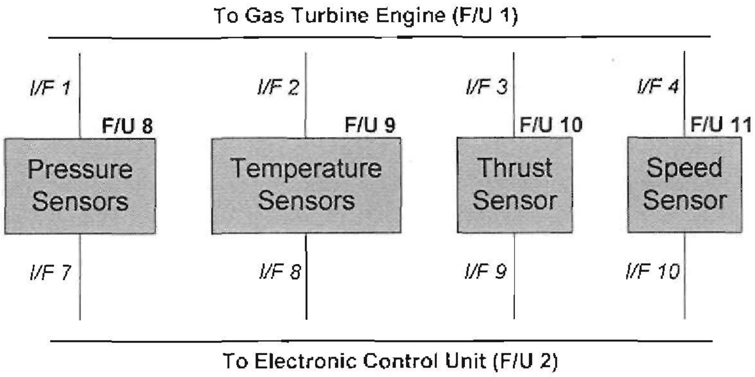


Figure 4.3.1 The Required Instrumentation Sensors

Figure 4.3.1 illustrates the required sensors for the system with their resulting interfaces. These sensors are discussed in the following sub-sections.

4.3.1 Temperature (F/U 9)

In these applications, robust temperature sensors should be used to determine the temperature at various places within the gas turbine engine. Temperatures up to a 1000°C need to be measured.

The K-type thermocouple was used to measure temperature. This sensor consists of a Nickel-Chromium alloy and Nickel-Aluminum alloy fused joint. When heat is applied to these conducting alloys, a potential difference is generated at the output. This voltage is in the µV range and needs to be amplified before it is read by an analog input of a MCU.

Thermocouples from WIKA Instruments (Pty) Ltd are used. These thermocouples (T1TEBKSS30) are type-K with an operating range of -40°C to 1000°C and 1.5°C sensitivity. Five of these thermocouples were purchased to measure the temperatures at specified locations. The cost of these five thermocouples is approximately R3 300. Figure 4.3.2 shows an image of the thermocouples.

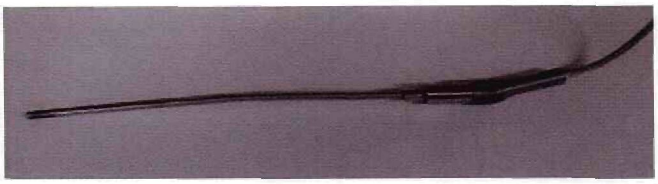


Figure 4.3.2 The Thermocouple from WIKA Instruments

The thermocouples are calibrated by WIKA Instruments (Pty) Ltd over a wide temperature range. These calibration certificates can be found in Appendix E.

4.3.2 Pressure (F/U 8)

Pressure sensors are needed to accurately measure the pressures within the gas turbine engine, up to a range of 250kPa (2.5 bar).

Five 0-250kPa sensors (S-10) from WIKA Instruments (Pty) Ltd were used. These are linear 4-20mA pressure transmitters and can therefore be easily implemented. The image below shows one of these pressure sensors.

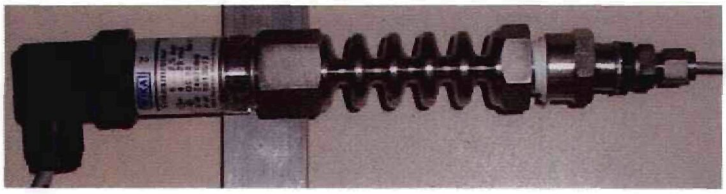


Figure 4.3.3 The Pressure Sensor from WIKA Instruments

The diaphragm of these sensors may not exceed 60°C and are therefore mounted in the bottom cabinet, connected to the gas turbine engine through 2 m long, 3mm thick capillary tubes, before entering a cooling department. This ensures that the air pressure measured cools down before it is applied to the sensor.

The pressure sensors are calibrated by WIKA Instruments at atmospheric pressure. The calibration certificates can be found in Appendix E. The total cost for the pressure transmitters, complete with capillary tubes and cooling elements, is approximately R12 000.

4.3.3 Thrust (F/U 10)

The thrust sensing mechanism is constructed by making use of strain gauges. The strain gauges are mounted at the bottom of the cantilever beam (see Figure 4.3.4). The force applied onto the beam is generated by the gas turbine engine mounted at the top of this cantilever beam.

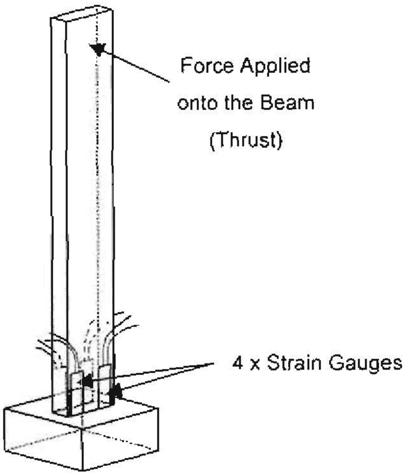


Figure 4.3.4 The Cantilever Beam with Strain Gauges [9]

The strain applied to the bar, which is generated by the thrust of the gas turbine engine, can be determined by these strain gauges. The resistance of the strain gauges changes relative to the change in strain.

Cost-free strain gauge samples were obtained from IEM. The strain gauges are mounted in a full bridge arrangement as illustrated in Figure 4.3.5, with two strain gauges (R1 and R4) on the one side, and two (R2 and R3) on the other side.

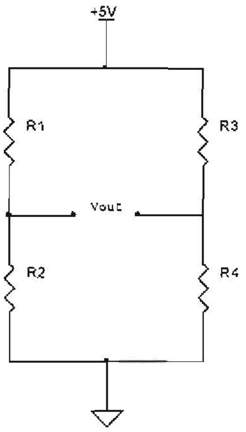


Figure 4.3.5 Strain Gauge Full Bridge Arrangement [10]

The beam is symmetrical and therefore this full bridge arrangement was implemented. If force is applied, the strain gauges on the one side is under tension (increased resistance) while the opposite side is compressed (decreased resistance). This change in resistance can then be determined by reading the output voltage with the ADC of an MCU, after the signal has been amplified.

The advantage of using the strain gauges in this full bridge formation is that temperature deviations do not influence measurements. If the tension in the beam increases or decreases due to temperature variations, this tension change is the same on both sides, which causes a cancellation effect when measurement is done.

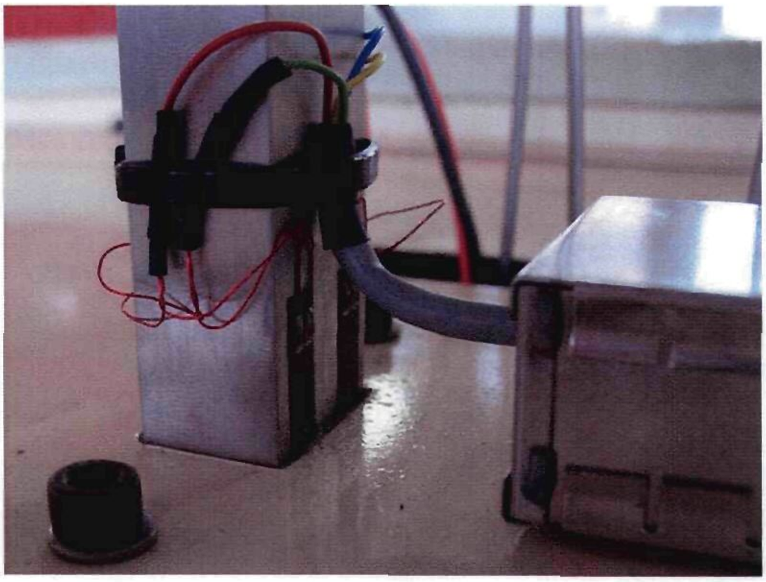


Figure 4.3.6 The Strain Gauges Mounted on the Cantilever Beam

Figure 4.3.6 shows the strain gauges that are mounted on the cantilever beam that interfaces with the thrust measurement unit (F/U 2.9) through screened cable. The detail design of the thrust measuring unit is discussed in section 4.4.1.2.

4.3.4 Speed (F/U 11)

The speed sensor is supplied with the gas turbine engine from the manufacturer. This is a linear hall-effect sensor that gives an analogue output according to the magnetic field around the sensor. A magnet is mounted inside the compressor blades by the manufacturer. This magnet causes a changing magnetic field that is sensed by the hall-effect sensor. The frequency of the changing magnetic field is proportional to the speed of the gas turbine engine.

Figure 4.3.7 shows the linear hall-effect sensor mounted at the compressor of the gas turbine engine.

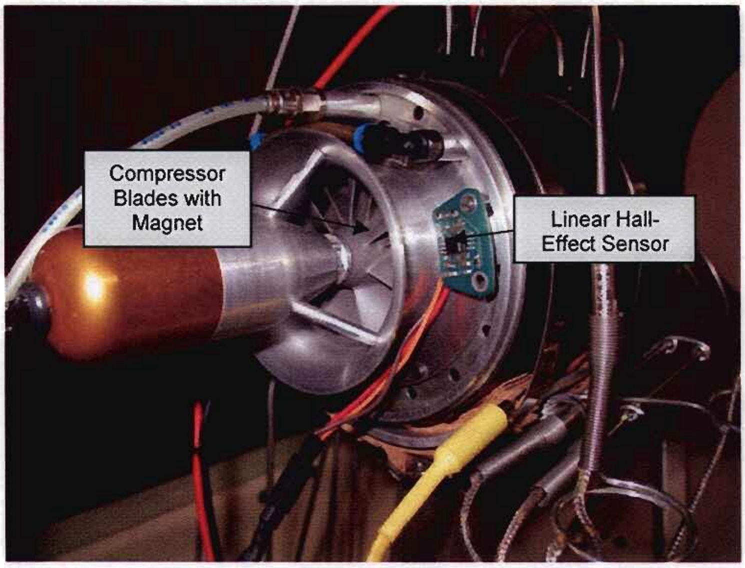


Figure 4.3.7 The Linear Hall-Effect Sensor, Mounted at the Compressor

The gas turbine engine, integrated with the instrumentation is shown in Figure 4.3.8.

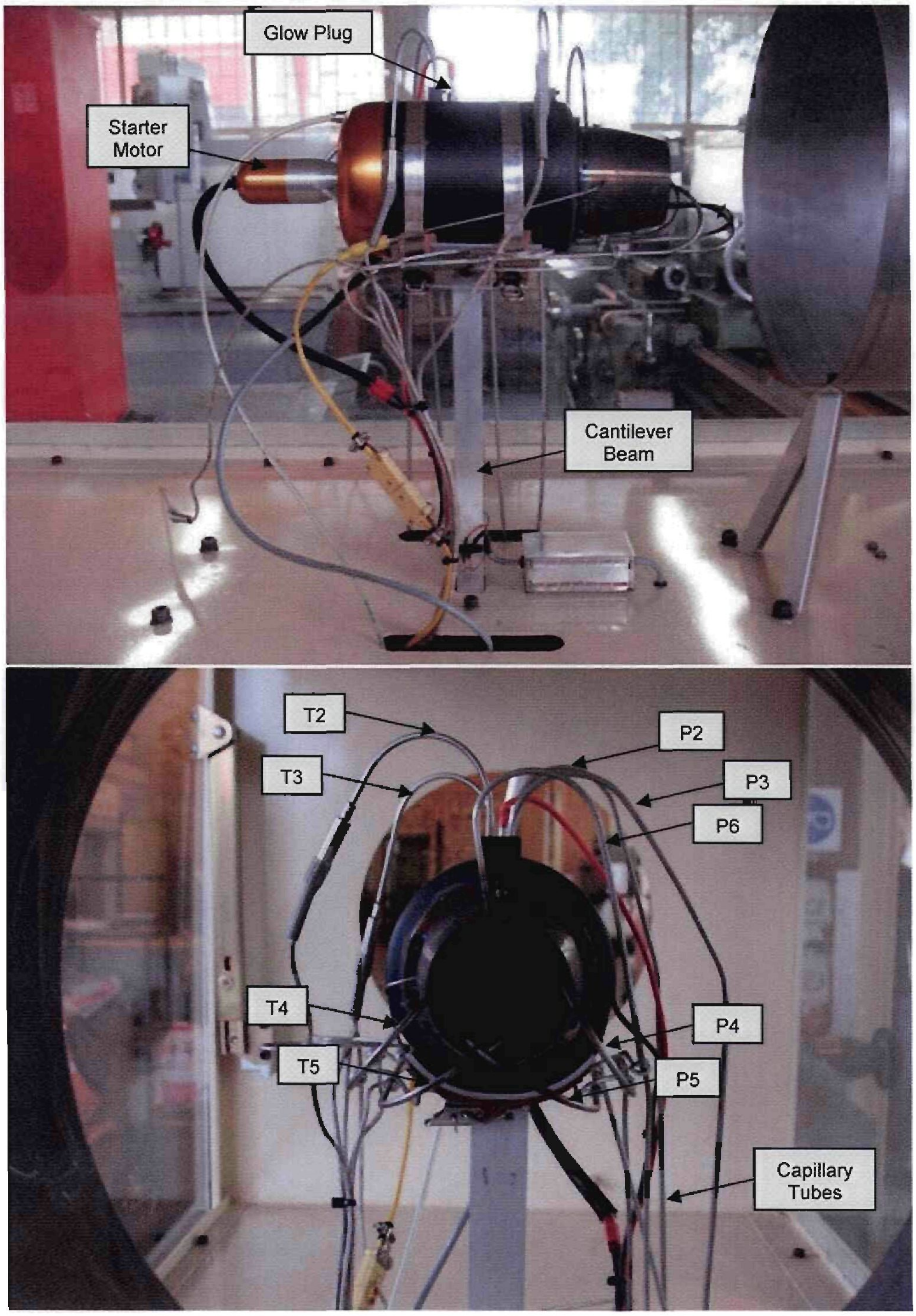


Figure 4.3.8 Gas Turbine Engine with Integrated Instrumentation

4.4 Engineering Development Model (EDM)

Generally, an Advanced Development Model (ADM) is built after an XDM. In this case, the ADM phase was skipped and could be done by virtue of a proper preliminary design.

The Engineering Development Model (EDM) provides a testable system that is fully integrated. This EDM is laid out on Printed Circuit Boards (PCB) to give repeatable and good EMC characteristics. Surface mount components were used as far as possible to limit the size of the PCBs.

4.4.1 Hardware Design

The electronic circuitry from the XDM was split into separate modules. This enables the designer to design the noise generating modules separate from the sensitive measuring units. The noise generating units can then be located as far as possible from the sensitive units to allow minimum distortions and a proper ground layout.

The hardware modules consist of the electronic control unit (F/U 2), thrust measurement unit (F/U 2.9), display unit (F/U 3.1), and power supply (F/U 5). The optimal design for each of these modules is discussed in the following sections.

4.4.1.1 Electronic Control Unit (F/U 2)

The architecture for the electronic control unit is shown in Figure 3.2.34. The functions of the central controller (F/U 2.10) is executed by using two separate MCUs on one board, with the first MCU acting as a master unit and the second as a slave. The reason for using two MCUs is the limitation of only two CCP modules per MCU, while four CCP modules are needed for the electronic control unit. This also allows the processing time to be halved.

The required hardware functions of this board are shown in the hardware abstraction layers (F/U 2.29.6 and F/U 2.30.3) of Figure 3.2.39. These are follows:

- MCU Master:
    - Read 5 x ADC inputs for the temperature sensors;
    - Read 5 x ADC inputs for the pressure sensors;
    - Read 2 x CCP modules to determine the fuel flow rate;
    - Drive 4 x digital outputs for diagnostic LED's and Bezel indication;
    - Read 3 x digital inputs for push buttons and switches;

  - Control the communication between modules and PC;

- MCU Slave A:
  - Drive 4 x digital outputs for relays;
  - Read 2 x CCP modules for speed sensing and control;
  - Read 1 x ADC input for control potentiometer;
  - Drive 2 x digital outputs for diagnostic LED's;
  - Read 2 x digital inputs for Start and Stop buttons;
  - Communicate with Master MCU;

These functions should to be implemented on the electronic control unit. The key functions and their implementations are discussed in the following paragraphs while the schematic of the whole design can be found in Appendix C.

Temperature Sensors (MCU Master)

The AD597 is a type-K thermocouple instrumentation amplifier from Analog Devices. This monolithic temperature set point controller is optimized for the use of elevated temperatures. The device compensates for the cold junction and amplifies the type-K thermocouple input to derive an internal signal proportional to temperature. This internal signal is then compared with an externally applied set point voltage to yield a low impedance switched output voltage. This device can be configured to provide an output voltage (10mV/°C) directly from the thermocouple [11].

The implementation of the AD597 IC is shown in the following figure.

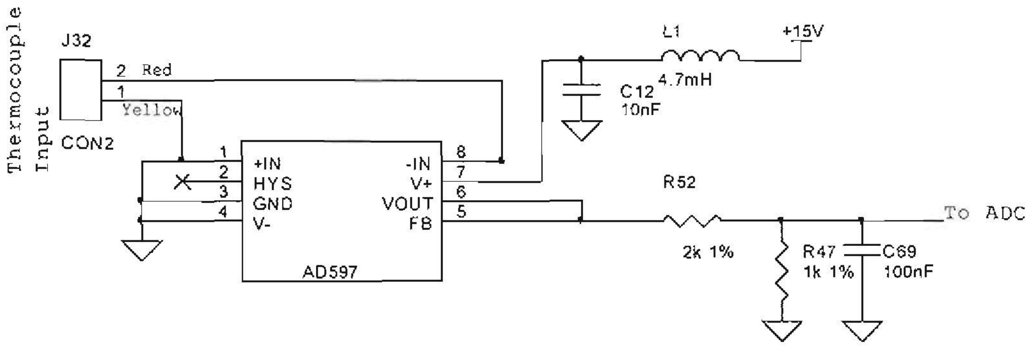


Figure 4.4.1 Thermocouple Instrumentation Amplifier Implementation

In the schematic above, decoupling is implemented at the source and an inductor is added for EMC and source stability. A 15V supply is used to drive the amplifier. This makes it possible to give up to a 15V amplified output at 1500°C. A voltage divider is used at the amplifier output to scale the output voltage from the amplifier down by a factor of three. With this scaling a maximum output of 15V (1500°C @ 10mV/°C), translates to 5V which is the maximum input voltage for the ADC of the MCU.

The AD597 IC needs to be as close as possible to the incoming wires of the thermocouples, in order to compensate correctly. Therefore, the ICs were placed next to the connector on the PCB layout.

Pressure Sensors (MCU Master)

The 0-2.5 bar pressure sensors from WIKA Instruments give a linear 4-20mA output. The sensor circuitry is applied as shown in the figure below:

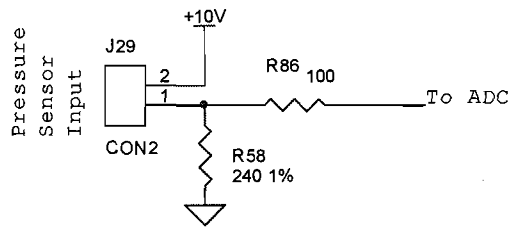


Figure 4.4.2 Pressure Sensor Implementation

The voltage across the 240 ohm resistor is measured to give an output voltage between 0.96V (0 bar) and 4.8V (2.5 bar). This output voltage is read by the ADC of the MCU in order to determine the pressure applied to the sensor.

Fuel Flow Rate (MCU Master)

The fuel pump is driven by the SCU (safety control unit). This is a pulse width modulated (PWM) signal in the range of 670Hz. The duty cycle is measured by two CCP modules of the MCU. The one CCP module is used to capture the rising edge of the PWM signal while the second CCP module is used to capture the falling edge. This enables one to measure the pulse width of the signal, and can the average voltage applied to the fuel pump be determined.

Digital Outputs (MCU Master)

Digital outputs were used to drive the diagnostic LEDs together with the Bezels. Two output pins is used for the bezels (green and red). The configuration for the Diagnostic LEDs are shown in Figure 4.4.3.

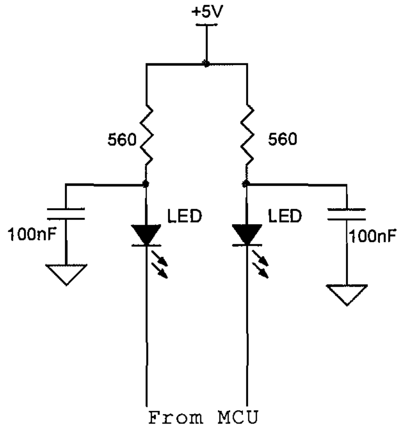


Figure 4.4.3 Diagnostic LED's Implementation

The 100nF capacitors are used to limit the noise generated if the LED's are switched at high slew-rates.

Digital Inputs (MCU Master)

Three buttons are connected to the Master MCU. These buttons are as follows:

- Mode Toggle switch – Diagnostics Mode / Run Mode;
- Logging Toggle Switch – Logging Enabled / Logging Disabled;
- Function Pushbutton – F1.

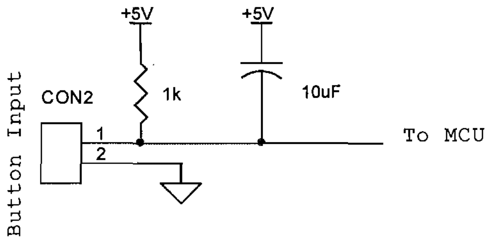


Figure 4.4.4 Switch / Pushbutton Implementation

Each of these buttons is implemented as shown in Figure 4.4.4. A pull up resistor is used together with a 10μF capacitor for debouncing purposes.

UART (MCU Master)

The UART of the master MCU is used to communicate to the slave MCUs. The TX pin of the master MCU is connected to the RX pins of the slave units but one needs to “AND” all the TX pins of the slave units with one another before it is fed to the RX pin of the master MCU. This “AND” operation is shown in Figure 4.4.5.

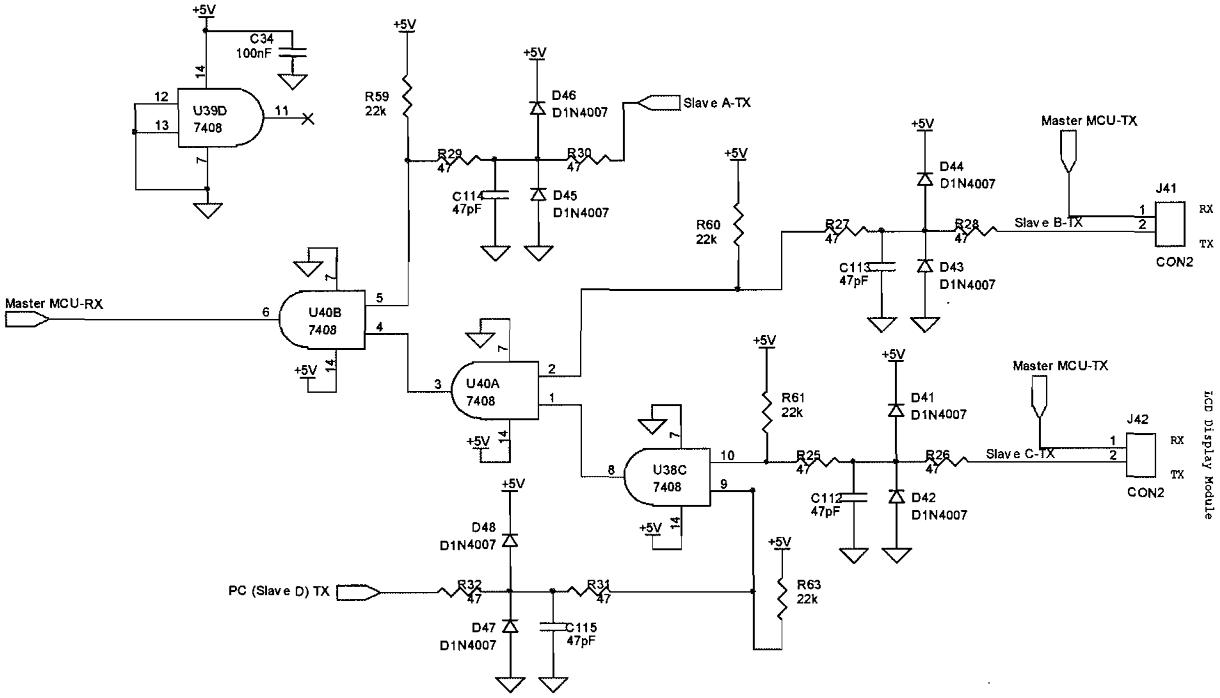


Figure 4.4.5 The “AND” operation for the communication from the Slave MCUs to the Master MCU

Protection is implemented from each incoming line in the form of back-to-back diodes. Pulse shaping is also done via the RC filters to limit EMI.

The communication voltage levels are kept to 5V between the modules. This can be done because the modules are fairly close to one another and higher voltage levels for communication would simply result in increased noise levels that will increase EMI. A MAX232 driver was used to communicate with the PC. The implementation of this driver is shown in the following figure:

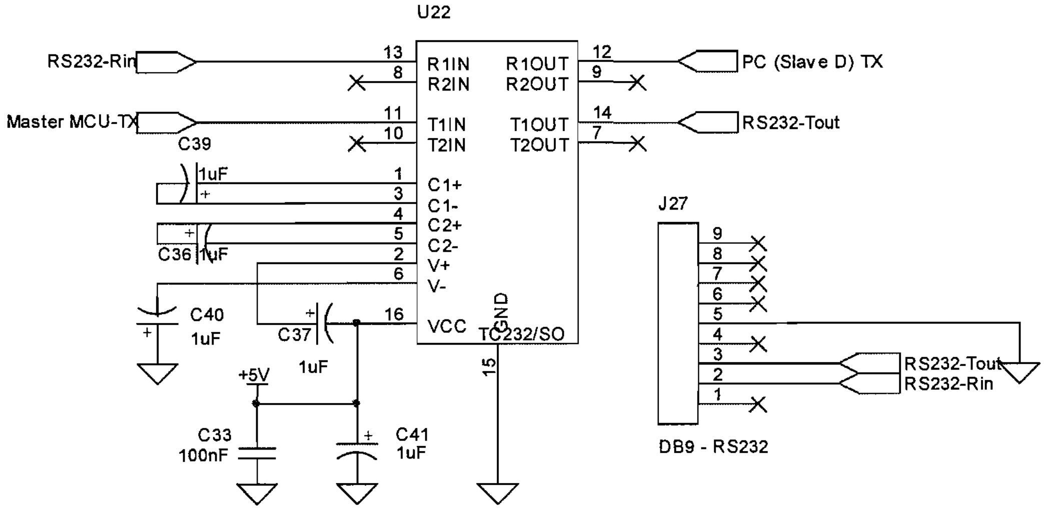


Figure 4.4.6 MAX232 Driver Implementation

A cable connects the PC with the DB9 connector, where pin 2 and pin 3 needs to be crossed, with pin 5 connected to ground.

Relay Outputs (MCU Slave A)

Relays are used to drive the solenoid valves in the gas and fuel lines. See F/U 14 and F/U 15 in Figure 3.2.32.

In Figure 4.4.7, the relay is switched from the MCU through a PNP transistor. An LED is also connected to show the status of the relay (on or off). Decoupling capacitors are connected at the power supply to the coil of the relay, with a freewheeling diode across the coil.

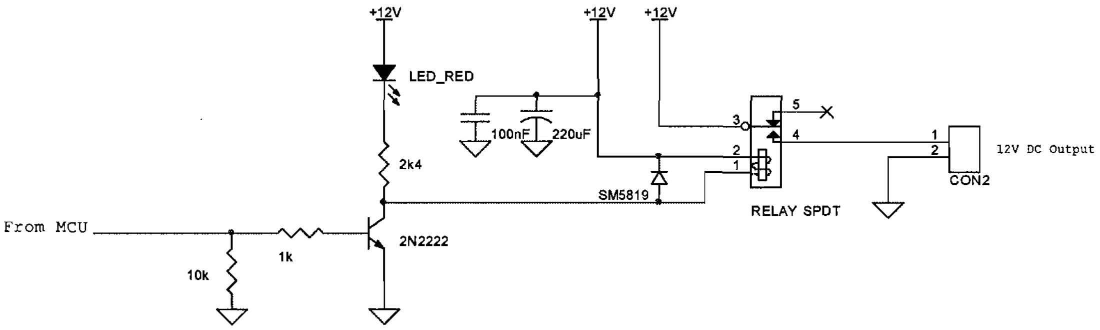


Figure 4.4.7 Relay Implementation Circuit

Four relays were implemented. Three relays are used as shown in the above diagram. The fourth relay is a high power relay that is used to isolate the ground of the glow plug. The implementation for this relay is similar to Figure 4.4.7, except that the common is not connected to 12V, and goes to the connector directly to form a dry contact.

Control Signal Generation (MCU Slave)

A control signal to the SCU is generated by slave A. The SCU uses this signal as the control input to control the SCU according to its specification. This signal could also be generated by an RF remote control, but in this application the control is done by wire to promote safety.

This signal needs to be generated by the slave A MCU. The remote is not used due to unwanted noise generated into the system. Figure 4.4.8 shows the hardware implementation from the MCU to the SCU. An RC filter was used to do the necessary pulse shaping to limit further noise generated by the signal and to limit EMI.

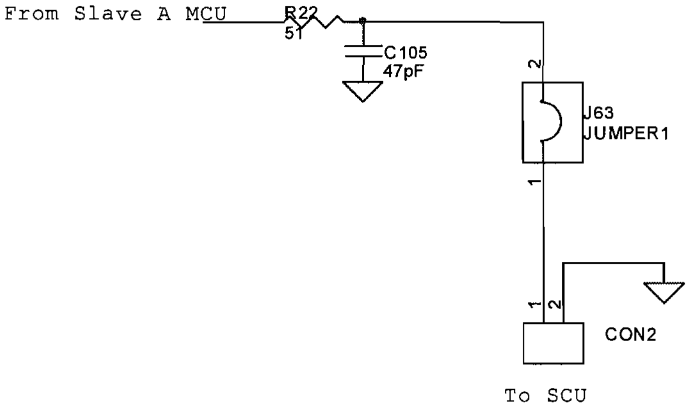


Figure 4.4.8 RF Control Signal Hardware Implementation

The RF remote control unit can still be used if the Jumper (J63) is removed, and the SCU is recalibrated. This is not recommended, especially when critical measurements are logged and analyzed.

Control Dial (MCU Slave A)

A dial with a potentiometer was used to set the parameters of the control signal. A single turn, high precision potentiometer was selected.

Figure 4.4.9 shows the hardware implementation for this potentiometer. The ADC value is read by the MCU and the duty cycle is controlled accordingly to generate the control signal.

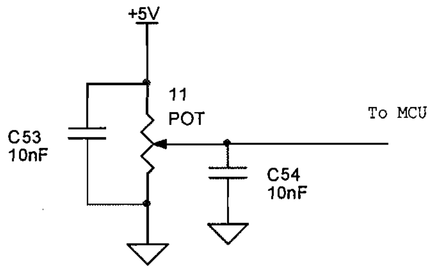


Figure 4.4.9 Control Potentiometer Implementation

Note that the potentiometer itself is located on the control panel, while the rest of the components are located on the PCB.

Speed Sensor (MCU Slave A)

A linear hall-effect sensor senses the speed of the turbine. The frequency of the pulse is determined by the CCP module, set up in capture mode. The speed of the gas turbine engine is then equivalent to the frequency of the input pulse from the linear hall-effect sensor.

It can happen that the sensor gets saturated which results in incorrect speeds. To correct this problem a strong (rare earth) magnet can be used to demagnetize the sensor. Circular movements, with the magnet facing the sensor, needs to be executed, first from the one side, then from the other.

Digital Outputs (MCU Slave)

Diagnostic LED's were implemented in the same way as done on the master MCU as shown in Figure 4.4.3.

Digital Inputs (MCU Slave)

Two digital inputs are used, one for the start button and the other for the stop button. The implementation of these buttons is the same as shown in Figure 4.4.4.

The emergency button works together with the stop button and is therefore connected in parallel. The difference between the emergency button and stop button is that the solenoid wires are run through the emergency button. This ensures that a solenoid cannot be open if the emergency button is pressed or locked.

Only key segments are discussed above and can the complete schematic for the electronic control unit be found in Appendix C.

The complete circuit is laid out on a PCB, divided into separate segments, each with a separate ground plane. All these ground planes are then joined at a single point close to the power supply of the board, which is generally the "noisiest" part of the circuit.

This ground layout is illustrated in Figure 4.4.10. The sensitive measurement segments, like the thermocouple instrumentation amplifier segment, are placed the furthest from the noisy parts i.e. the power supply, communication driver and relays. This ensures that the sensitive measurement circuits are the least affected by the noise generating segments.

The common ground point is then grounded to the chassis. Only this point should be connected to the chassis, and nowhere else should any electronic modules be connected to the chassis, else ground loops will be generated, influencing the stability of the system.

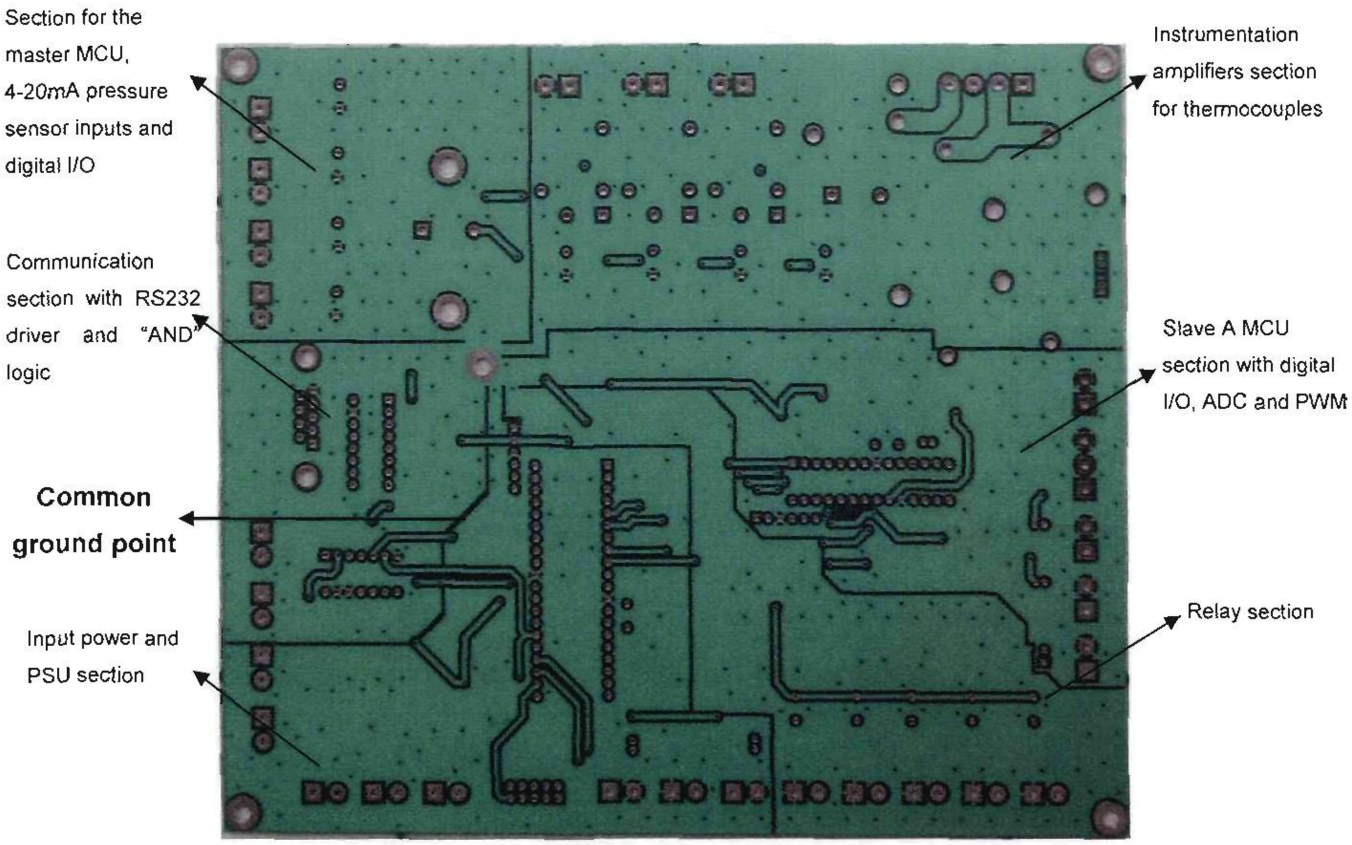


Figure 4.4.10 Electronic Control Unit PCB Ground Layout

Note that the PCB image in Figure 4.4.10 is mirrored across the horizontal plane in order to correspond with the image in Figure 4.4.11.

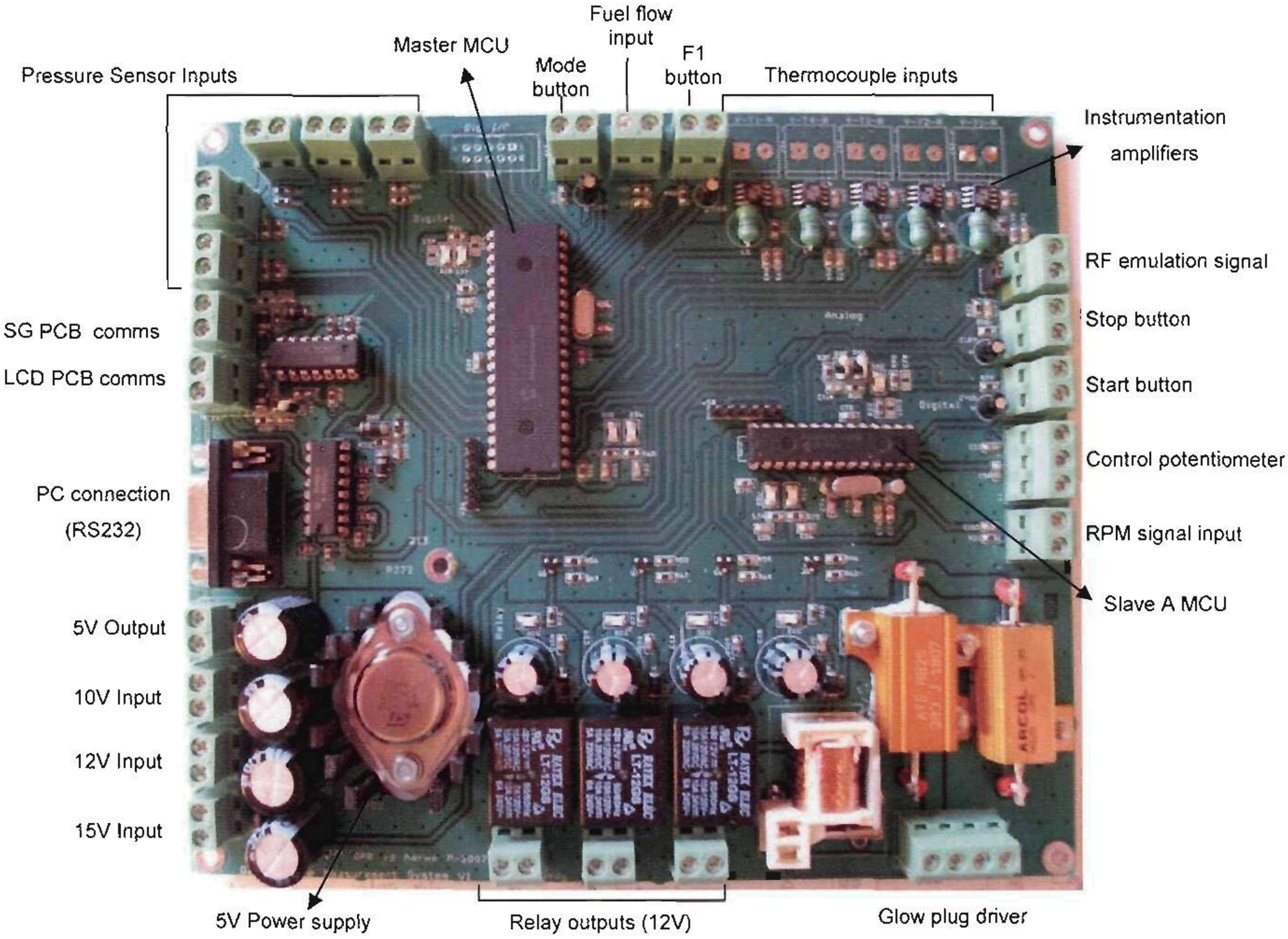


Figure 4.4.11 The Electronic Control Unit PCB Circuit

The complete populated circuit is shown in Figure 4.4.11. This forms the electronic control unit. All inputs and outputs are also marked - these interface with the rest of the system.

4.4.1.2 Thrust Measurement Unit (F/U 2.9)

The thrust measurement unit is a separate module to measure as cleanly in terms of EMI as possible. This module is located as close as possible to the cantilever beam and is connected to the strain gauges with short wires. The signal from the strain gauges are in µV's which means that noise affects this signal, especially if the signal runs through long wires before amplification is done. The signal is measured and the thrust is determined by the MCU (Slave B) before the data is sent serially to the master MCU.

An AD627 instrumentation amplifier was used to amplify the signal received from the strain gauges. The gain can be set externally by the resistor between pin 1 and pin 8. The following equation can be used to calculate the gain [12]:

$$R_G = \frac{200k\Omega}{(Gain - 5)} \tag{4.1}$$

A gain of 271.6 is achieved if a 750Ω resistor is used for R_G. The amplifier circuit implementation is shown in Figure 4.4.12.

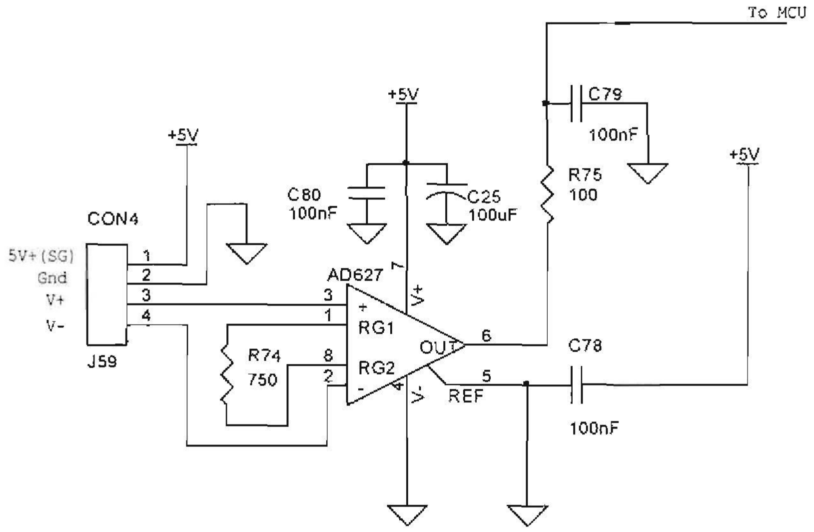


Figure 4.4.12 The Instrumentation Amplifier Implementation

The input voltage to the thrust measuring unit is 15V. From here, the voltage is regulated to 5V to supply power to the MCU and amplifier IC. This ensures that a steady supply is used to supply the amplifier. A multi-turn potentiometer was also added to adjust the offset when the unit is calibrated. The complete schematic for this unit can be found in Appendix C.

The ground plane of the PCB was split into two segments. This is shown in Figure 4.4.13 that illustrates the bottom layer of the PCB. The sensitive measuring segment has its own ground and is joined at one point (see bottom right corner) to the rest of the board's ground, which could be a more "noisy" ground. This helps to keep the supply to the measuring segment as smooth as possible.

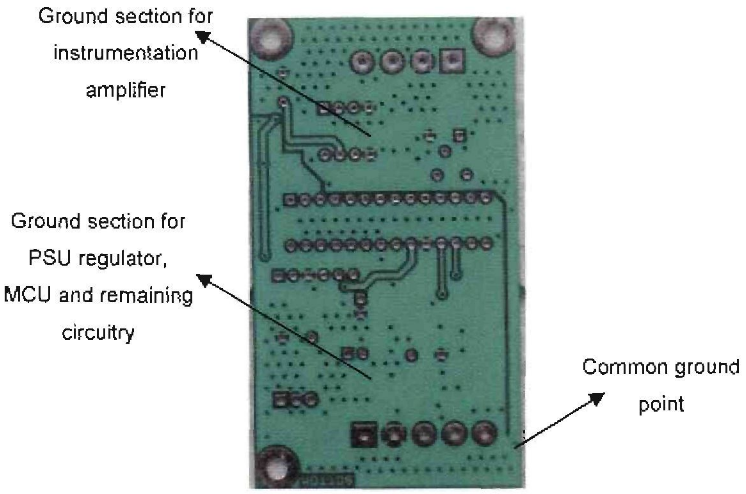


Figure 4.4.13 Thrust measurement Unit PCB Ground Layout

Figure 4.4.14 illustrates the implemented circuit contained in a tin-plated enclosure. This box is mounted next to the cantilever beam. The strain gauges are mounted in a Wheatstone bridge formation and are also visible in the photo.

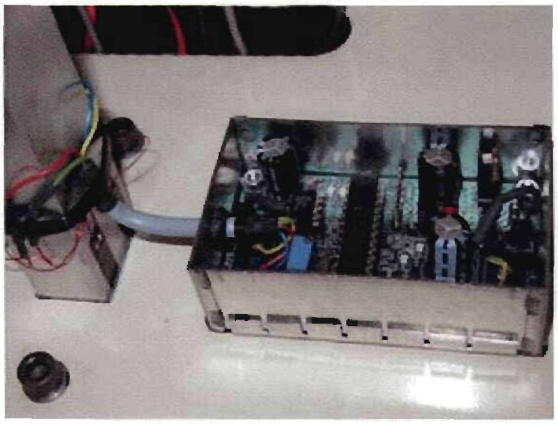


Figure 4.4.14 The Contained Circuit with the Strain Gauges

The mild-steel tin plated enclosure is grounded through the screen of the screened cable and runs to the electronic control unit, where the screen is grounded to the common ground point (see Figure 4.4.10). The tin plated enclosure is also electrically isolated from the test bench by using plastic spacers. This prevents a ground loop and keeps the ground to the test bench's chassis common to one single point at the power supply of the electronic control unit.

4.4.1.3 Human Machine Interface (F/U 3)

The human machine interface is a control panel, used for the mounting of the buttons and displays to enable the operator to read and control the unit. The functional architecture of the buttons, switches, controls, and displays that were implemented on the human machine interface, are shown in Figure 3.2.36.

The complete assembled human machine interface is shown in Figure 4.4.15. A stainless steel laser cut-out was used. Screened cable was used for interfacing with the electronic control unit and the screen of the cables is connected to a common ground at the electronic display unit (see Figure 3.3.1 for the ground layout).

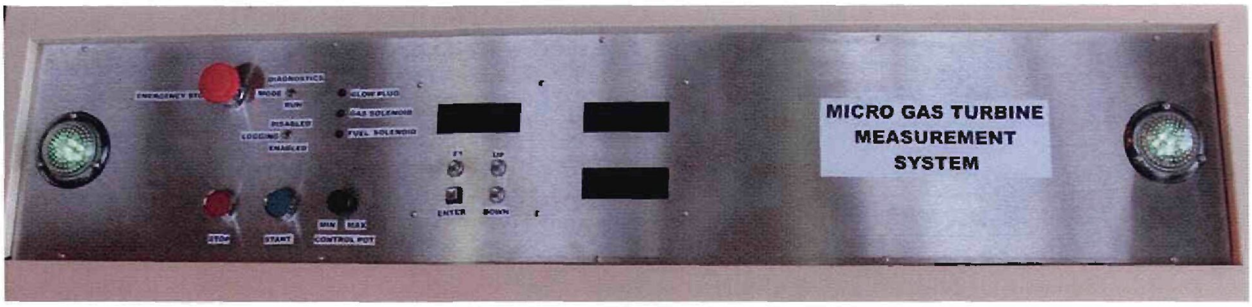


Figure 4.4.15 The Implemented Human Machine Interface

This control panel is easy to use and easy to access. This enables the operator to operate the system with minimum effort. The detail design for the display unit is shown in the following section.

4.4.1.4 Display Unit (F/U 3.1)

This display unit forms part of the human machine interface and is used for data display. Instructions are displayed to guide the operator and to indicate the system's status. All the data measured are also displayed on this unit. This includes pressures, temperatures, thrust, speed, and fuel flow.

This unit was designed to be separated from the rest of the electronic circuitry due to noise generated by the LCD displays. This unit can then be mounted separately, away from the measuring modules to limit disturbance when measurements are made.

This unit consists of a MCU (slave C) that receives data to be displayed from the master MCU on the electronic control unit. A 5V regulator was added to supply power to the components because the input power is 12V. The MCU interfaces with two 4x20 LCD's and diagnostic LED's. Protection was placed on the incoming communication lines.

The design for this unit is straightforward and the detail schematic may be found in Appendix C.

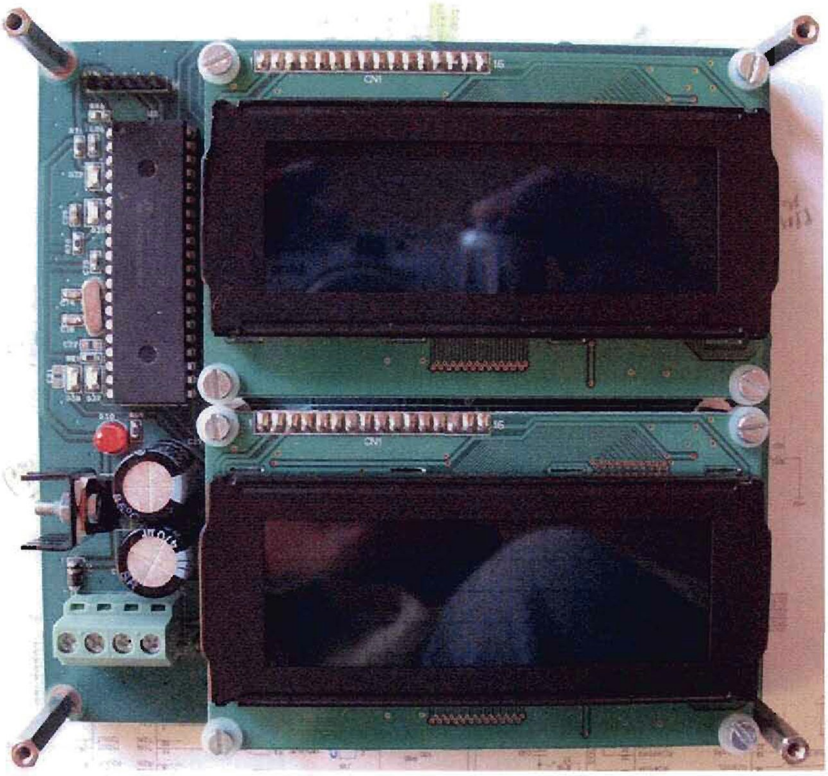


Figure 4.4.16 The LCD Display Unit

Figure 4.4.16 shows the complete display unit with LCDs mounted. This unit is mounted on the control panel. The communication lines should be connected to the electronic control unit, while power should also be supplied from the 5V power supply.

4.4.1.5 Power Supply Unit (F/U 5)

The power supply unit is a separate module designed to generate all the required voltages to drive the rest of the system. The architecture for the power supply unit is shown in Figure 3.2.38. The supply consists of two transformers that reduce the incoming voltage (220Vac) to 18Vac. Two separate transformers were used to generate a high current supply. One transformer supplies the noisy parts of the system while the other transformer is used to power the more sensitive low current measurement modules. This provides additional EMI filtering.

After each supply, a low pass filter was added to limit unwanted frequencies, followed by AC to DC conversion. This is done through 6A bridge rectifiers, 2200µF capacitors and 78 series regulators (TO3). The TO3 regulators were mounted on heat sinks.

Protection was added in the form of slow blow fuses (3A) together with poly-switches for thermal shutdown. Two PI-type EMI filters were also added at the input to filter common mode and differential mode noise.

The schematic for the power supply unit can be found in Appendix C. The complete unit is shown in Figure 4.4.17.

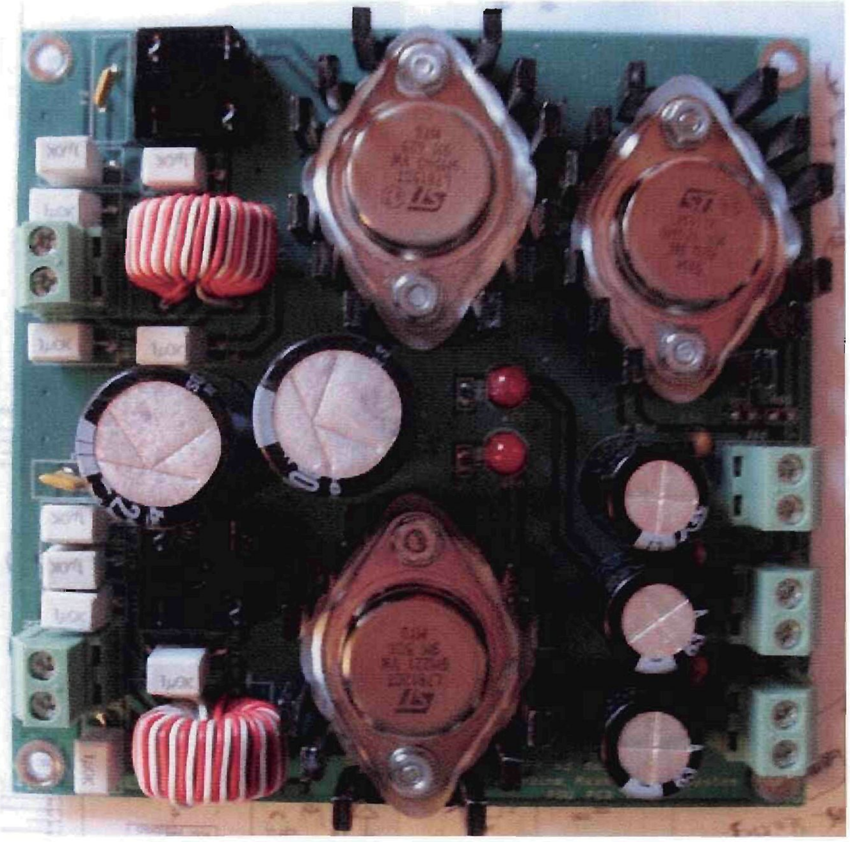


Figure 4.4.17 The Power Supply Unit

A separate power supply was required to supply power for the starter motor and glow plug. This supply needs to be able to supply high currents up to 10A at 7Vdc.

A switch-mode power supply is used. This is a buy-in item because the design of such a supply is beyond the scope of this project. The S-100-7.5 PSU from MEAN WELL was selected. This supply can deliver 100 Watts, with 7.5Vdc output at a continuous current rating of 13A. This supply has built in short-circuit and overload protection. Figure 4.4.18 shows an image of this supply.

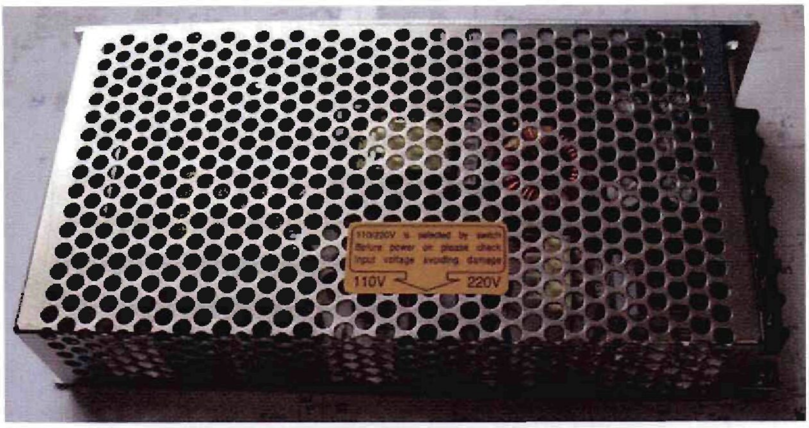


Figure 4.4.18 The S-100-7.5 Switch-mode Power Supply

This switch-mode power supply is mounted in the bottom part of the cabinet, away from the rest of the electronic circuitry. This minimizes the effect of the noise generated by this supply on the rest of the electronic circuitry.

4.4.2 Firmware Design

The firmware design for the MCU of each module is discussed in this section. The firmware architecture, as shown in Figure 3.2.39, is broken down one more level in the form of state diagrams. From these diagrams all the states of the firmware (main routines) can be followed. Each state, numbered as a functional unit, is mapped to the source code in Appendix F.

4.4.2.1 Master Firmware (F/U 2.29.5)

The state diagram for the main routine of the master MCU is shown in Figure 4.4.19.

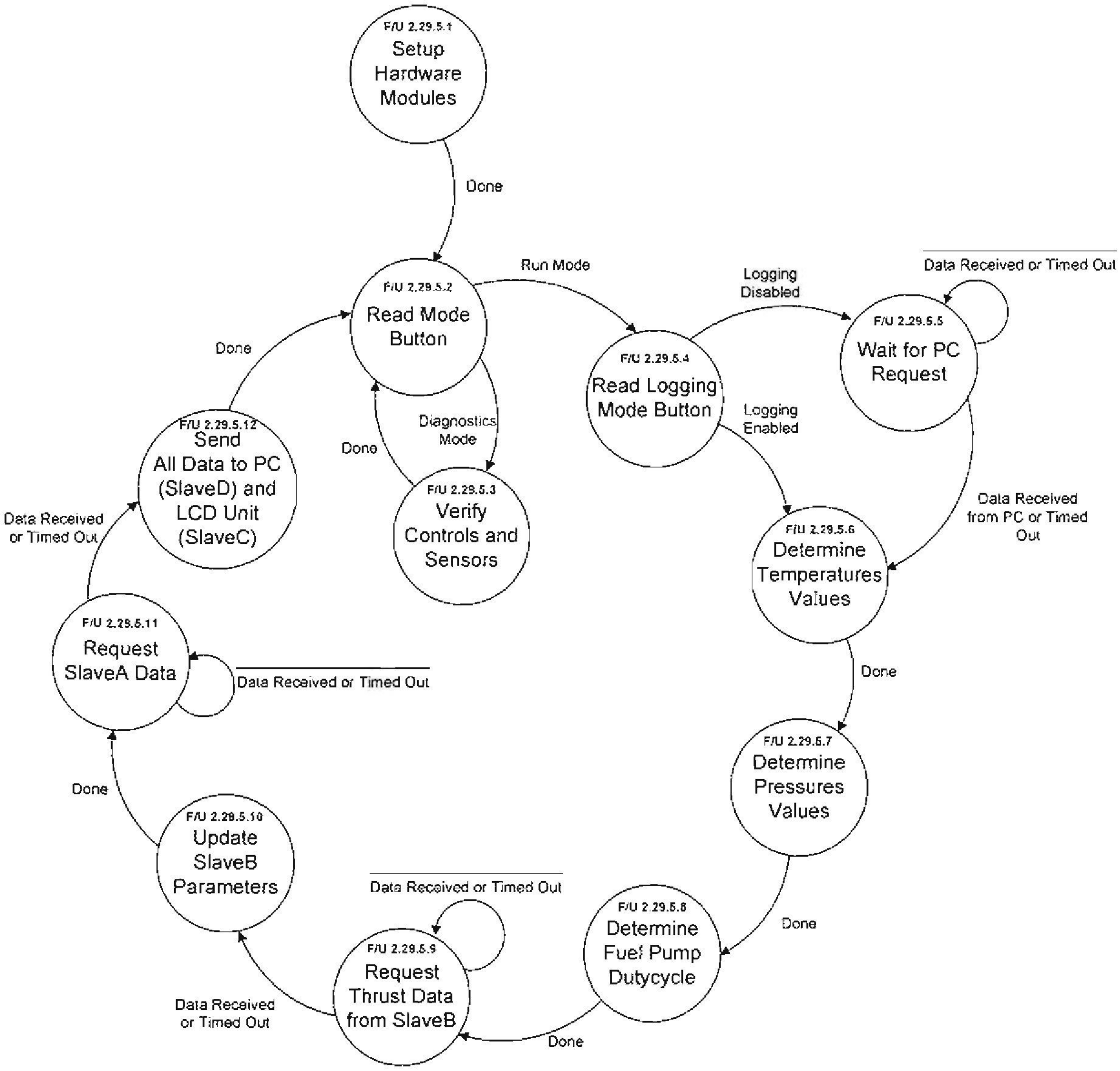


Figure 4.4.19 Master MCU Firmware State Diagram

The master MCU controls the communication between all the modules. A reflection diagram of the data flow is illustrated in Figure 4.4.20. Note that the reflection diagram shows the data flow when the logging is enabled. If logging is disabled from the control panel, no request is sent from the PC and the data flow starts with the request from the master to slave A.

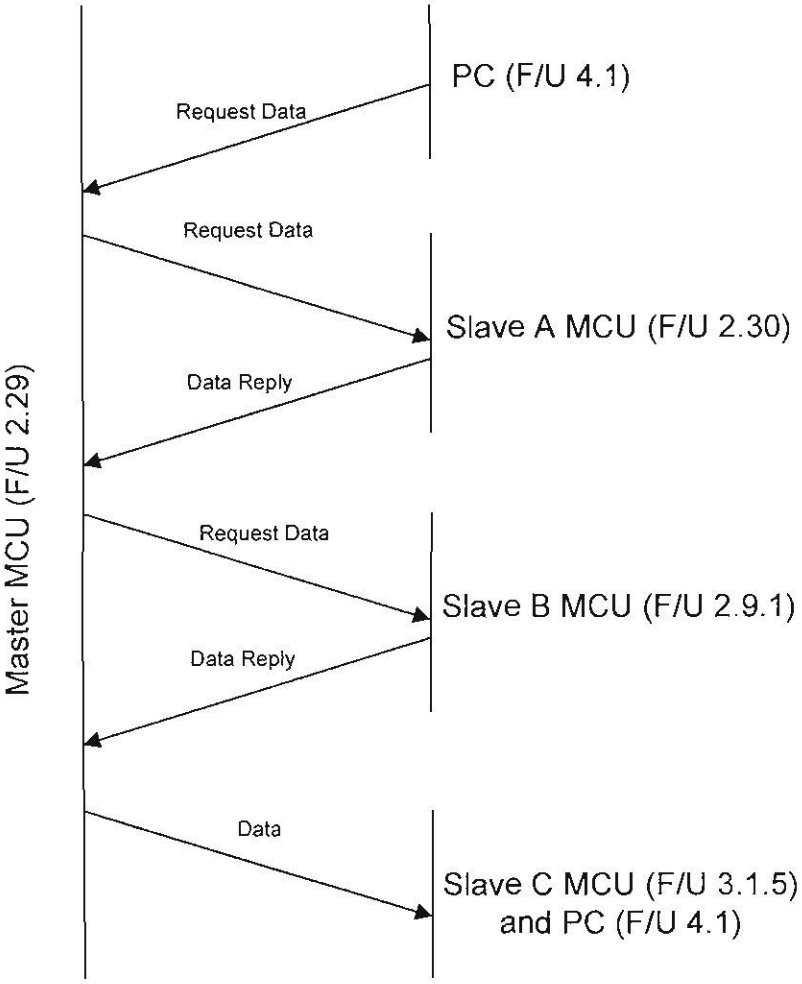


Figure 4.4.20 Data Flow between Modules when Logging is enabled

When slave A and Slave B receive requests from the master, a reply is sent with the required data in a known format. If the master receives no data, a timeout occurs. This ensures that the next state can be entered. In order to update the display unit and the PC, data is sent to these modules in a known format for display and/or logging purposes.

4.4.2.2 Slave A Firmware (F/U 2.30.2)

The state diagram for slave A is shown in Figure 4.4.21. All the required inputs are read and the data is analyzed and sent to the master MCU when requested. The main functions for this MCU are to read the start and stop buttons, set the control signal according to the dial, and determine the speed of the gas turbine engine.

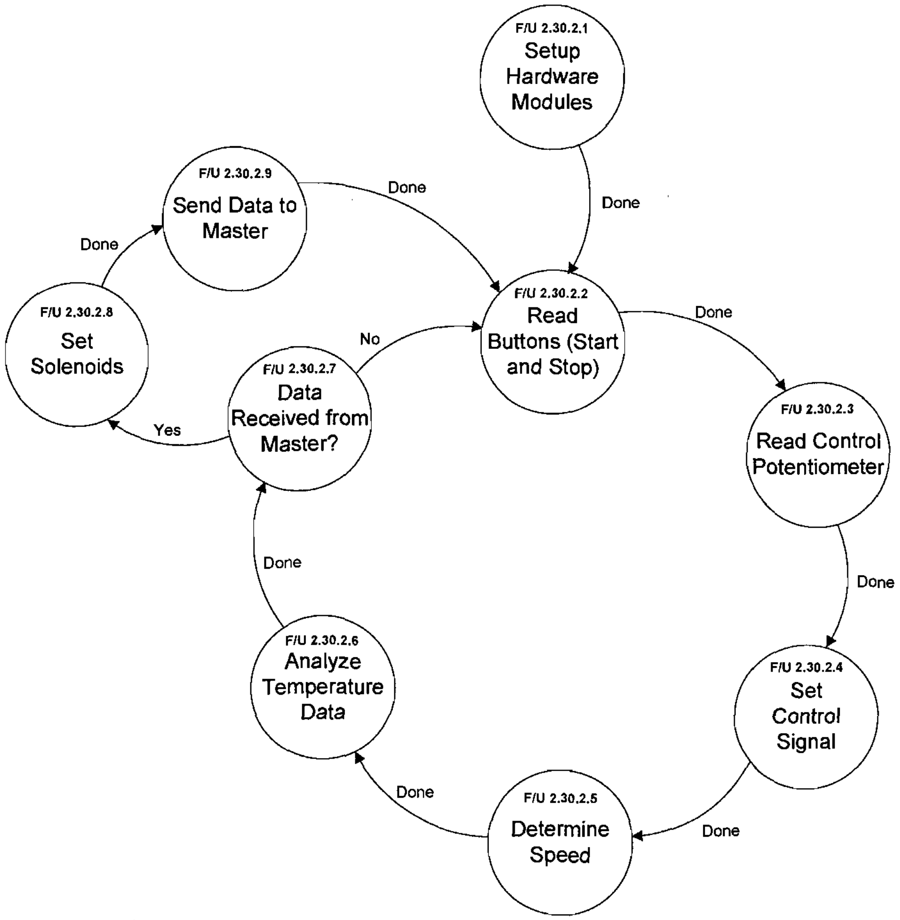


Figure 4.4.21 Slave A Firmware State Diagram

4.4.2.3 Slave B Firmware (F/U 2.9.1.2)

In Figure 4.4.22, the state diagram for slave B is shown. This MCU reads the amplified signal from the strain gauges and converts this signal to the applied force on the cantilever beam. This data is sent to the master when requested.

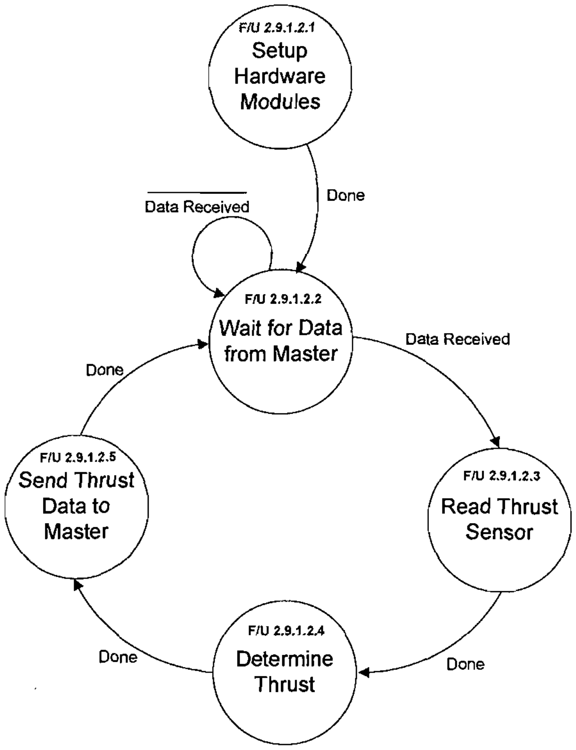


Figure 4.4.22 Slave B firmware State Diagram

4.4.2.4 Slave C Firmware (F/U 3.1.5.2)

Figure 4.4.23 shows the state diagram for slave C, the MCU of the display unit. The function of this MCU is to update the LCD displays when data is received from the master.

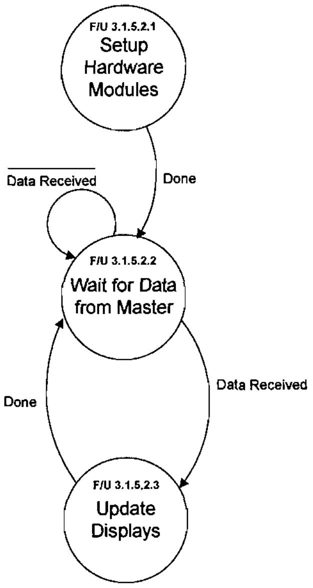


Figure 4.4.23 Slave C Firmware State Diagram

More detail regarding the firmware of these modules can be found in Appendix F, where all the source code for the firmware modules can be found.

4.4.3 Software Design

A program was written in MATLAB® to capture the data and display this data in graph format and in real-time on the PC. The state diagram for the software design is shown in Figure 4.4.24.

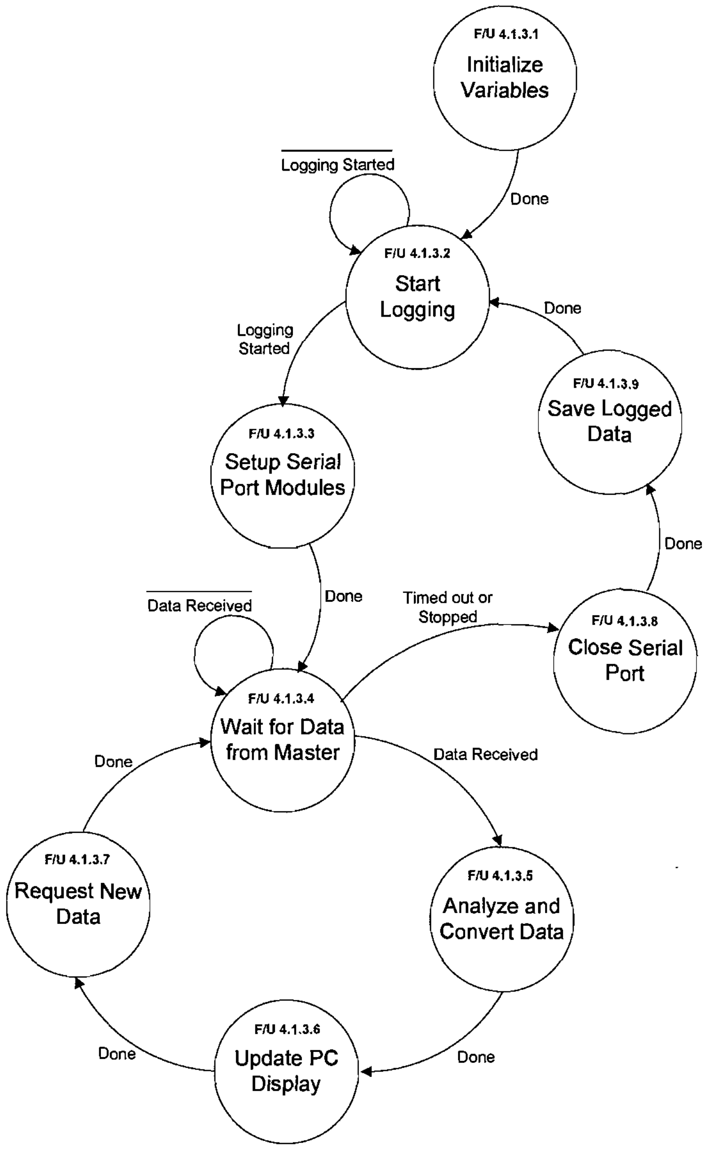


Figure 4.4.24 The MATLAB® Software State Diagram

A request is send from the PC to the master MCU. After the Master MCU has collected all the data, a reply that contains the required data is sent to the PC. The PC software analyzes the data and does conversions where necessary before updating the screen.

The software is written in the form of a graphical user interface (GUI), as shown in Figure 4.4.25, to make the system as usable and user friendly as possible. The operator should ensure that the PC is connected to the system. The com port of the

PC needs to be selected (default is COM1), and the system should be set up in the correct mode on the control panel (mode = run and logging = enabled). See O/F 3.0 and O/F 4.0 in the System Operational Analysis for more detail.

Logging and real-time display can be initiated by pressing the "Start Logging" button. The yellow TX and RX indicators in the "Comms Setup" panel will flash green to show that the communication is active. As data is received from the electronic control unit, all the parameters as shown in Figure 4.4.25 will be updated to show the status of the system in real time. The speed, temperatures, and pressures are also plotted in graph format for an optimized visual interpretation. Further graphs can be plotted and analyzed once the data is saved into spreadsheet format.

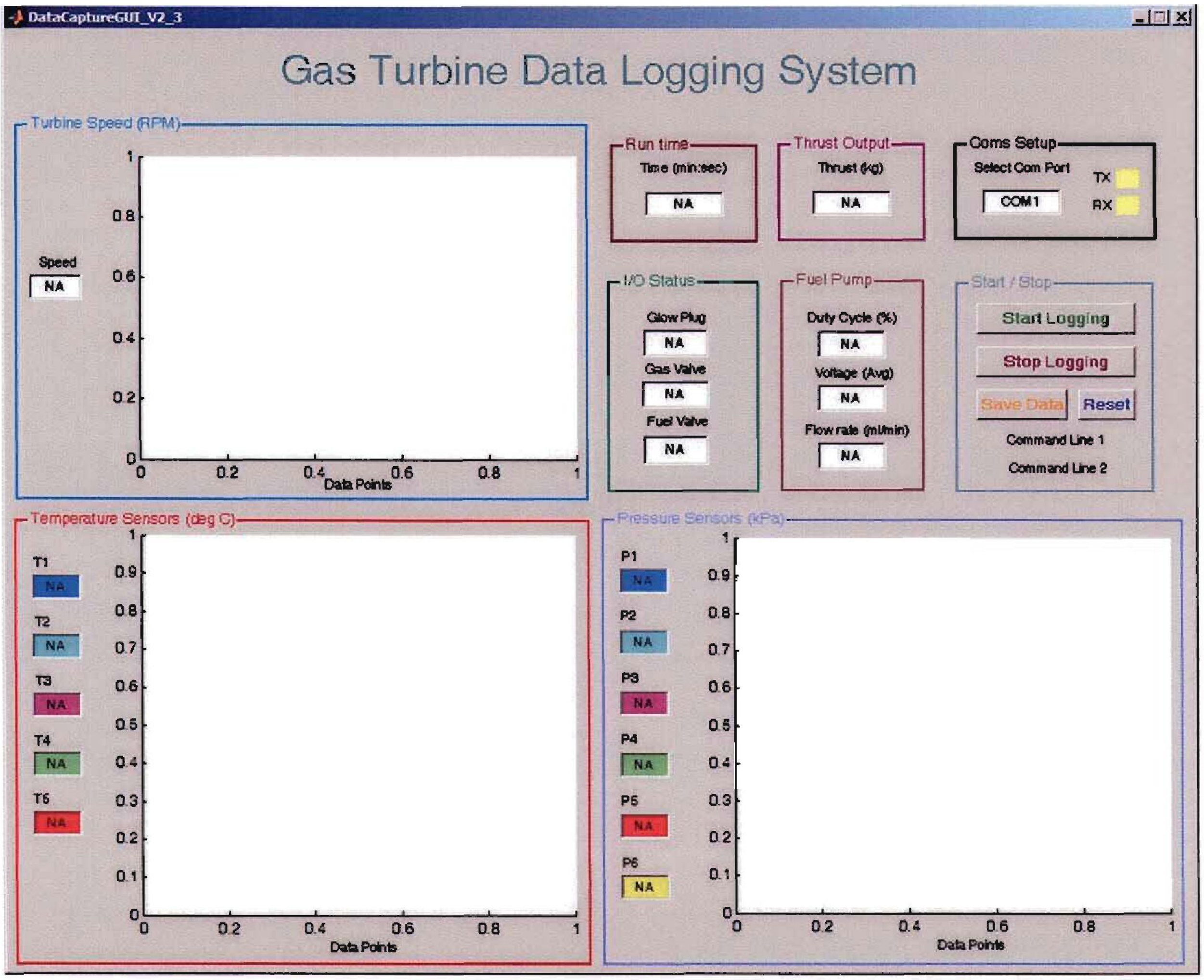


Figure 4.4.25 Data Logging Software GUI

Once data has been logged, logging can be stopped using the "Stop Logging" button. The data needs to be saved for further analyses by pressing the "Save Data" button. The data is saved to "DataLogV2-GUI.xls" in the same directory where the program is run from.

The "Reset" button can be used to reset the displays and clear all the logged parameters. Note that when using this button, the logged data is lost if the data was not saved.

With this GUI, the system can be easily monitored in real time. Verification of this software, and all the measured values, is done in the following chapter.

Chapter 5
Testing and Verification

5.1 Introduction

Testing and verification is an important phase during this development. In this chapter, all the measurements that were taken from the sensors are verified. The test setup procedure is explained for each device under test (D.U.T.) and the accuracy of each measurement is determined.

The results obtained from the system while it was running can be found on the accompanying CD (see Appendix F). Two separate run operations have been executed and data was logged. The results from Run1 will also be used as a reference for verification and testing of separate modules and the system as a whole. The plotted results for Run2 can be found in Appendix D. Note that the speed sensor's data is used as a reference for the plotted data.

5.2 Speed Sensor (F/U 11) Verification

The implementation of the speed sensor circuitry and firmware can be tested by generating the output signal of the speed sensor with a signal generator. The signal generator is set up to provide a signal of 50% duty cycle. The duty cycle is not critical because the frequency of the signal is measured by the electronic control unit to determine the speed. The speed measured by the electronic control unit, displayed on the LCD, is compared to the input frequency generated by the signal generator. The speed measured, should be the frequency of the input signal in Hz, multiplied by 60 to get the RPM.

This verification procedure was done over 25 test points, from 0 RPM (0 HZ) to 120 000 RPM (2 kHz) with 5 000 RPM (83.3 Hz) increments between data points. The results obtained showed that the signal is measured correctly and that the conversions are correctly done.

Due to the wide range of speeds generated by the gas turbine engine, the speed value is rounded to be accurate within 100 RPM. This rounding minimizes unwanted digit fluctuations of the tenths and units, which can be irritating to the user's eye.

Figure 5.2.1 shows the logged data of the speed sensor during the operation of the gas turbine engine. A maximum speed of 109 000 RPM is logged. The response of these speeds can be mapped to the run time logged at each data point (see Appendix F for the complete logged table). The speed sensed at the end of the operation relates to the cooling phase, where the starter motor is used to cool down the system.

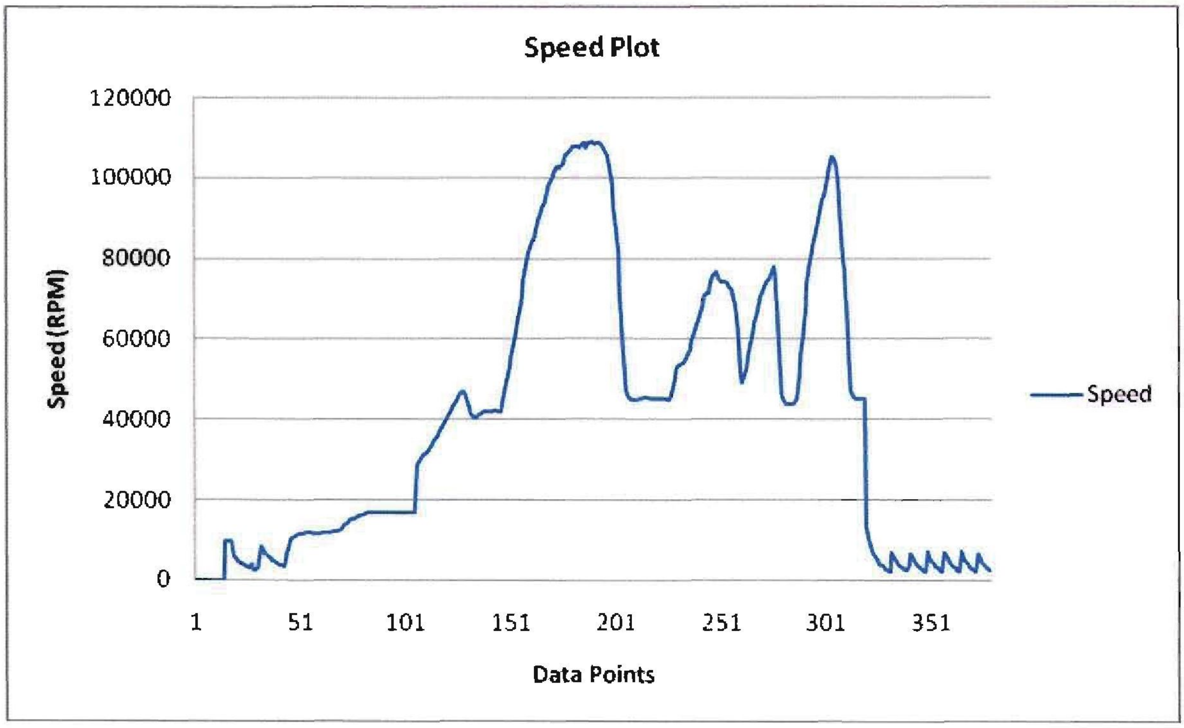


Figure 5.2.1 Speed Measurements Logged during Operation

This speed plot will be also be used as a reference in the following plots to verify the other measurements obtained during the system operation.

5.3 Temperature Sensor (F/U 9) Verification

Temperature values were obtained from the system as explained in section 4.4.1.1. Verification of these measurements was done by comparing the measured temperature values with an existing digital thermometer. Although no certainty can be given that this thermometer is 100% correct, it was used as a reference to verify **only** if hardware and firmware **implementations** were done correctly. Water was heated and both the D.U.T. (thermocouple) and the digital thermometer were placed in the water. After a settling time was allowed, the values were taken in order to determine the verification of the sensor. This process was repeated for each thermocouple from 10°C to 90°C with increments of 10°C.

Once all five thermocouples have been verified, a maximum of 3°C in deviation was observed from the D.U.T relative to the digital thermometer. Note there could also be an error made by the digital thermometer, and therefore are the % error determined from the calibration certificates (see Appendix E) supplied by the manufacturer where proper calibrated instrumentation were used for calibration purposes. The measuring range for the D.U.T. is from -40°C to 1000°C, relating to an error of less than 0.3% over the measuring range, as a maximum of 3°C deviation was obtained from calibration certificates. Also note that the maximum deviation generally appears at the higher end of the measurement range from 700°C upwards. This error of 0.3% was acceptable.

This verification process is limited because the measured temperatures were only verified up to 90°C, but the true error was assumed to be given on the calibration certificates supplied by the manufacturer. Therefore, this process is still acceptable because the main purpose of this verification procedure was to ensure that the sensors were correctly implemented, that is, to ensure that the hardware and firmware implementations were correct.

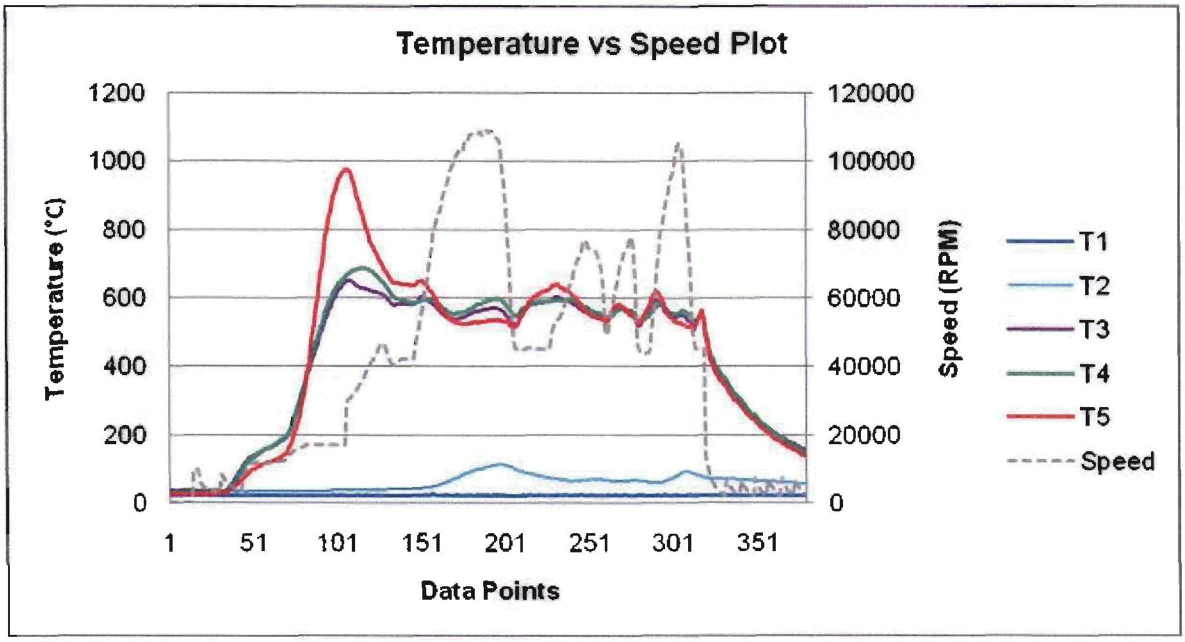


Figure 5.3.1 Temperature Measurements Logged during Operation

Figure 5.3.1 illustrates the plot of the temperatures obtained during the operation of the gas turbine engine. The speed of the gas turbine engine is used as a reference, indicated on the secondary axis. Temperature measurements of almost 1000°C were obtained at the exhaust exit (T5) during the startup. Thereafter, as the mass flow increased through the engine this probe cooled down to the 600°C region.

5.4 Pressure Sensors (F/U 8) Verification

The procedure followed to verify the pressure sensor measurements is similar to the temperature sensor verification procedure. A known pressure was applied to each pressure sensor's probe inlet when disconnected from the turbine. A compressor was used to generate the pressure with a 4mm tube that connected the sensor probe to the compressor. The reading from the compressor's pressure gauge was used to verify the readings obtained from the pressure sensors. Pressures were applied from 0 kPa up to 200 kPa, with 50 kPa increments. The maximum expected pressure was 100 kPa when the system was running.

The pressure gauge from the compressor was used to indicate the applied pressure. This is an analogue gauge and it was therefore difficult to determine the exact pressure. The range of the gauge is up to 1100 kPa, and therefore a large tolerance for the required measured range existed. The ideal would have been to use a digital pressure gauge, but the readings obtained from the analogue gauge were still acceptable because the sensors were calibrated at the factory. The main purpose of this verification procedure was to verify if the implementation of the sensors were done correctly.

The obtained readings from the analogue display matched the measurements of the measuring system for each D.U.T. (P1 to P6), which shows the sensors were correctly implemented. According to the calibration certificates, the accuracy of the pressure sensors is 0.5%. This relates to a maximum error of 1.25 kPa, which is acceptable for this application.

The obtained pressure values from the system, while the gas turbine engine was running, are shown in Figure 5.4.1. The speed is again used as a reference between the plotted data. More information regarding this data can be found in Appendix F.

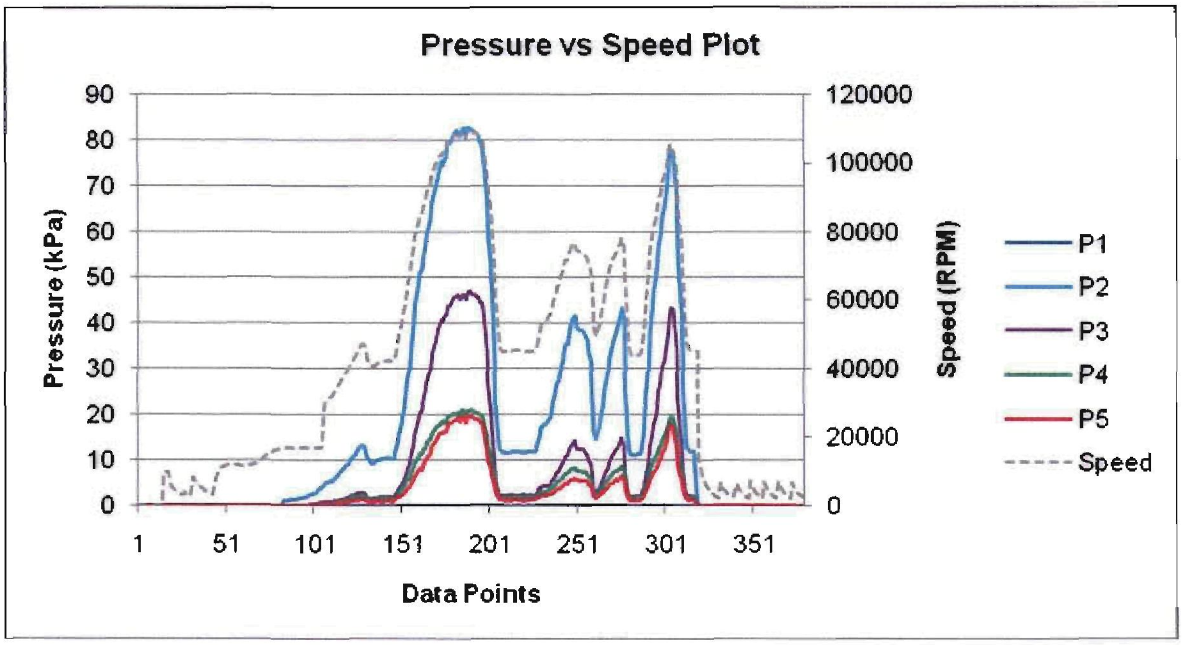


Figure 5.4.1 Pressure Measurements Logged during Operation

P1 shows the atmospheric pressure and therefore stays constant at 0 kPa. The pressure is the highest at the compressor exit (P2). A maximum value of 82.8 kPa is obtained for P2 at a speed of 109 000 RPM. The difference between P2 and P3 shows the pressure drop across the combustion chamber, with P4 the pressure measured at the turbine exit. P5 shows the pressure at the exhaust exit.

More accurate calibration can be done by using calibrated laboratory equipment. This shall be done when calibrated equipment becomes available. As for this work, the functional capability was demonstrated and the performance adjustment can be performed before the system is fully commissioned.

5.5 Thrust Sensor (F/U 10) Calibration and Verification

The thrust is determined by means of strain gauges since an appropriate load-cell could not be sourced. The thrust sensing mechanism is thus not an off-the-shelf item. The thrust sensing mechanism should be properly calibrated and tested to ensure that thrust measurements are valid and that the implementation was done correctly.

In order to calibrate the thrust sensor, a force was applied to the beam by means of a winch system. The range of the applied force starts at 0 kg up to 12 kg, with 0.5 kg increments. The applied values were taken down and compared to the measured values. The offset was determined and used to compensate the measurements. This process was repeated until satisfactory results were obtained.

After the thrust measurement sub-system was successfully calibrated, the sub-system was verified. The verification results are shown in Figure 5.5.1. The maximum error obtained from these results is 0.2 kg, giving a maximum error of 1.67%.

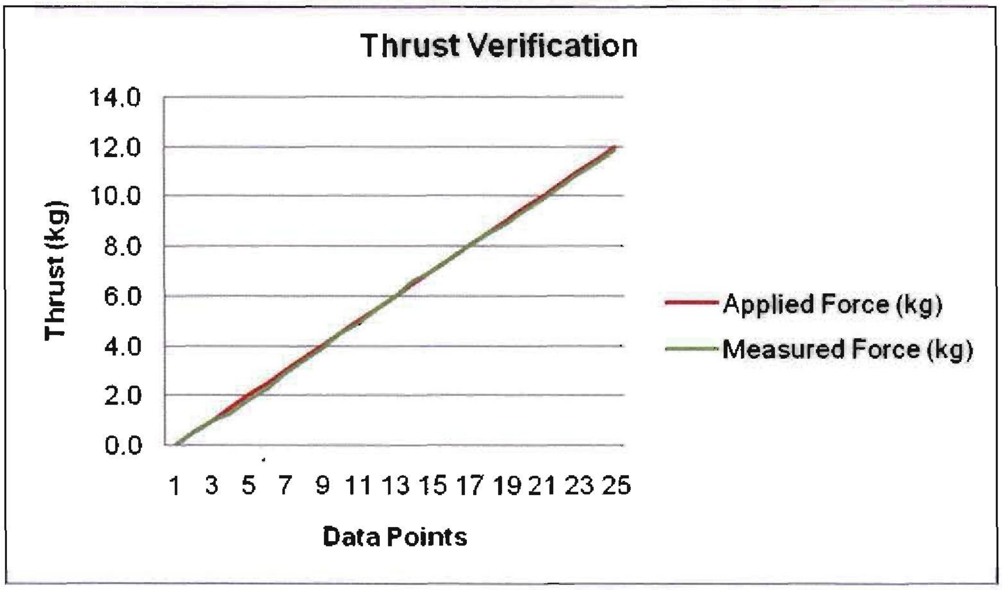


Figure 5.5.1 Thrust Sensor Verification Results

Figure 5.5.2 shows the measured data of the thrust sensor logged during the operation of the gas turbine engine. A maximum thrust of 7.1 kg is obtained at 109 000 RPM.

The data plot of the thrust measurements in the figure below is not as smooth as the other measurement plots (see Speed plot in Figure 5.2.1). This data noise is due to some rattling on the cantilever beam when the unit is operated at high speeds.

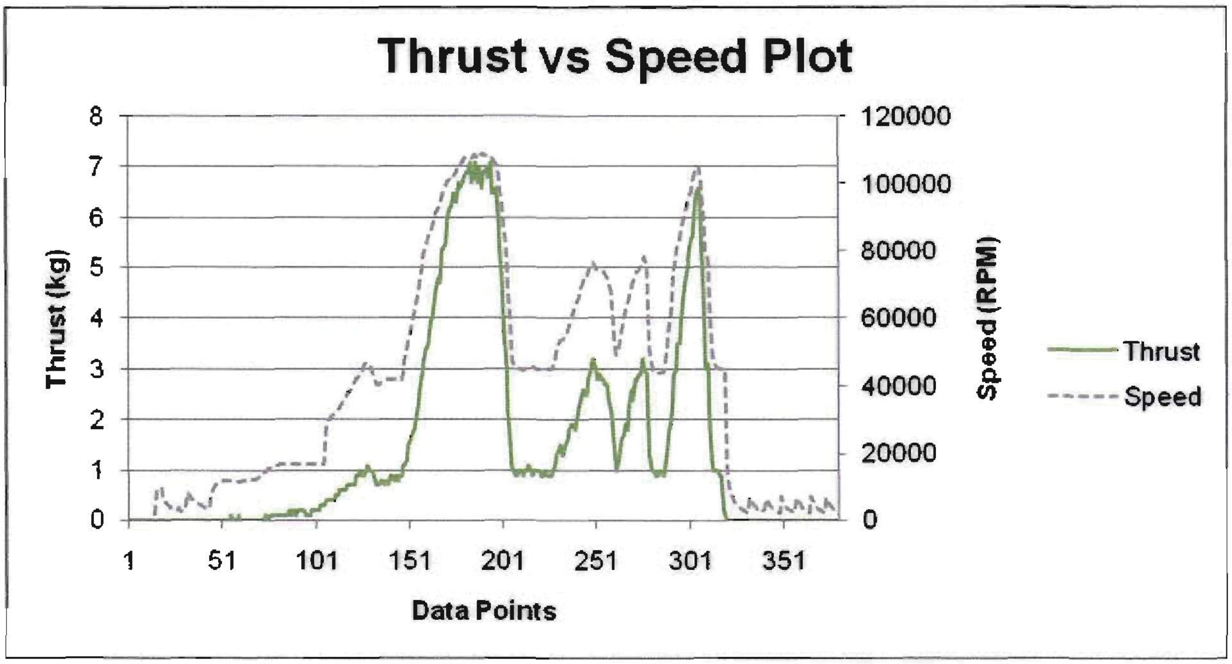


Figure 5.5.2 Thrust Measurements Logged during Operation

5.6 Fuel Flow (F/U 16) Output

A PWM signal is used to control the fuel pump. This signal is generated by the SCU, and measured by the electronic control unit in order to determine the fuel flow rate. The average voltage of this signal is deterministic, and is converted to a fuel flow output in ml/min.

After the fuel pump had been characterized, the required hardware and firmware implementations were done in order to determine the fuel flow. This output of the fuel flow is shown in Figure 5.6.1. This data was logged during the operation of the gas turbine engine and relates to the logged data shown in Figure 5.2.1. From this data a maximum of 500 ml/min of fuel was consumed at the maximum logged speed of 109 000 RPM.

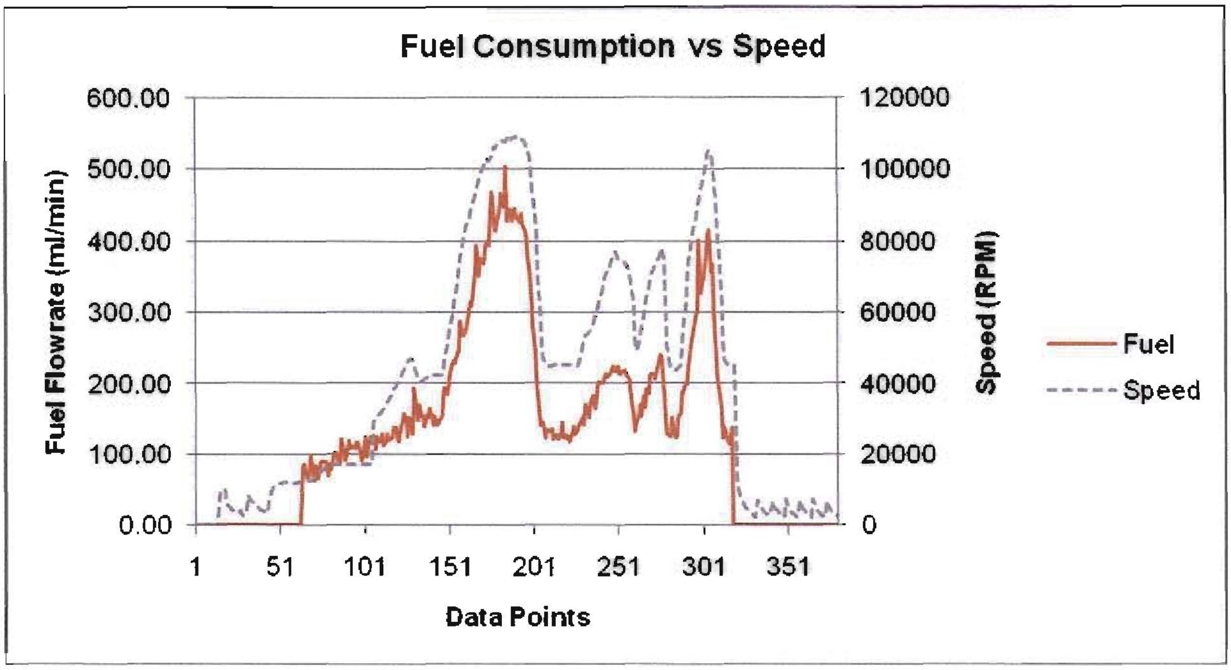


Figure 5.6.1 Fuel Flow Rate Logged during Operation

5.7 Control Signal Verification

The turbine is controlled via the control signal. In order to verify this control signal, a digital storage oscilloscope was used to verify the correctness of this signal as shown in the figures below.

A control signal was generated at 52 Hz (see Figure 5.7.1) with a duty cycle related to the control input. The stop button (F/U 3.7), start button (F/U 3.8) and control dial (F/U 3.9) were used to set the duty cycle of this signal. At system power up, or when the stop button is pressed, the duty cycle is set to 5.7% as shown in Figure 5.7.2. When the start button is pressed, the duty cycle is set to 6.6% (see Figure 5.7.3). Thereafter, the duty cycle is controlled via the control dial from 6.6% to 10.6% as illustrated in Figure 5.7.4.

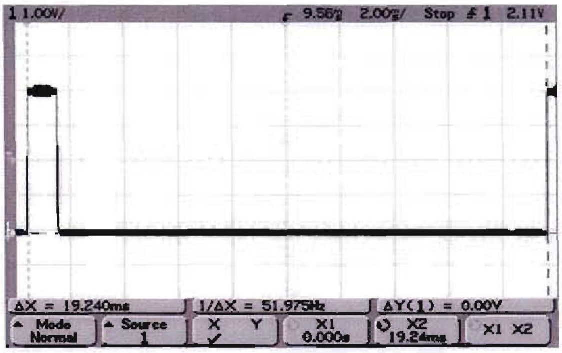


Figure 5.7.1 Control Signal Frequency Measured as 52 Hz

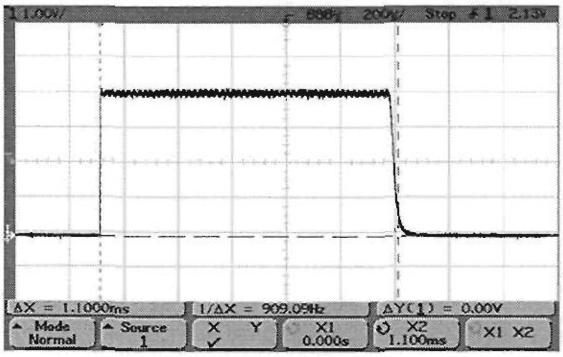


Figure 5.7.2 Control Signal Duty Cycle at 5.7%

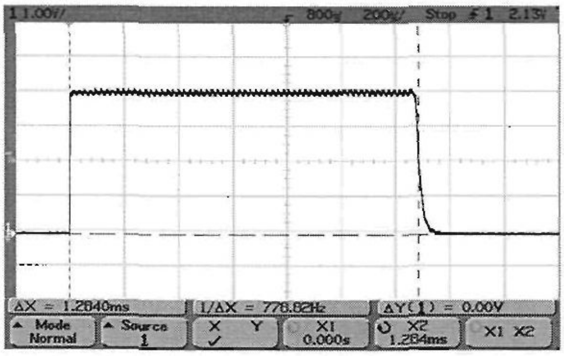


Figure 5.7.3 Received Control Signal Duty Cycle at 6.6%

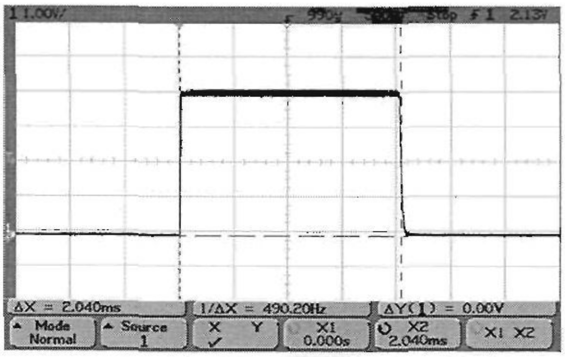


Figure 5.7.4 Control Signal Duty Cycle at 10.6%

This control signal is used to control the speed of the gas turbine engine. Figure 5.2.1 shows how the speeds are varied by using the control dial.

5.8 Control Panel (F/U 3) Verification

The operation of the control panel can be verified through the diagnostics mode (M/F 14.0) built in test (BIT) procedure. The operational flow of this procedure can be found in section 3.2.1 where the operational analysis of the system is discussed.

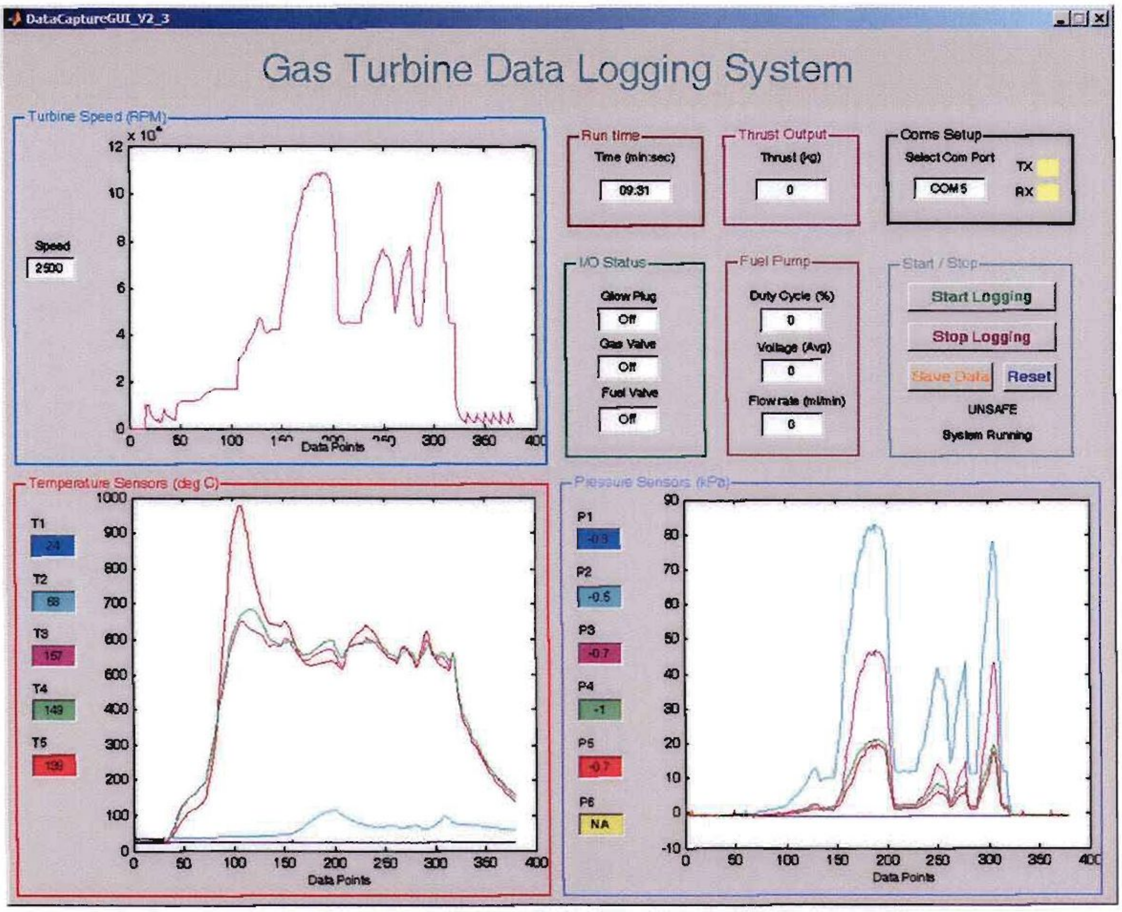
Most buttons and switches can be tested in this procedure. This includes the stop and emergency stop button, start button, logging mode switch, control potentiometer, together with the gas and fuel solenoid valves.

This test procedure is built in as a separate mode of the system and can therefore be used during maintenance to ensure that all the controls are fully functional.

5.9 Software (F/U 4.1)

The written software was implemented and verification was done to ensure that all the data are logged, displayed, and saved correctly. This verification was done on each sensor individually. The sensor was triggered (by adding heat / pressure / force etc) and through visual inspection it was observed that the data was displayed and logged correctly in the right place, i.e. file creation process worked.

Figure 5.9.1 shows the graphical user interface of the software during the operation of the gas turbine engine. All data is correctly shown in real time display, and saved in spreadsheet format when the "Save Data" button is pressed.



Speed 2500

Time (min:sec) 09:31

Thrust (kg) 0

Select Com Port COM5

Glow Plug Off

Gas Valve Off

Fuel Valve Off

Duty Cycle (%) 0

Voltage (Avg) 0

Flowrate (ml/min) 0

UNSAFE

System Running

T1 24

T2 68

T3 157

T4 149

T5 139

P1 -0.3

P2 -0.5

P3 -0.7

P4 -1

P5 -0.7

P6 NA

Figure 5.9.1 Software GUI Display during Operation

The sampling rate is determined by two factors, the performance of the PC and the amount of data logged. Because the data is shown in real time, the PC display needs to be updated after each sampling point before the next data sample is requested from the electronic control unit. This is a time consuming procedure and as the number of data points increases, the matrix containing the data increases, which results in an increase in time to update the display.

Data was logged on a PC with an Intel Pentium 4 processor and with 512 mb RAM. Samples were taken twice per second when the logging was started. The sampling rate decreases as the data matrix increases, resulting in a sampling rate of 1.5 samples/sec after 5 minutes. This data samples with the appropriate run time can be found on the accompanying CD (see Appendix F).

This is an acceptable data-sampling rate for this application. The gas turbine engine is also not usually run for long during demonstrations, and the run time should be less than 10 minutes for demonstration purposes.

If, however, a faster sampling rate is required another version of the software was written and implemented. With this alternative option, the data is not visually displayed on the screen but still logged and saved in spreadsheet format. This minimizes the processing time and speeds up the sample rate. With this alternative, a sample rate of 3 samples/sec can be achieved when the logging is started. This sampling rate is maintained throughout the entire logging operation. The same PC was used for both tests. The data for this test can be found in Appendix F, Run2.

Another alternative is to use a better PC with a faster processor and more memory. This would speed up the sampling rate significantly for both programs written.

Chapter 6
Conclusion

6.1 Introduction

This chapter concludes this project. The delivered system is shown and discussed together with future possibilities for this project. The conclusion is formed at the end of this chapter.

A video clip can be found on the accompanying CD (Appendix F) that shows the operation of the gas turbine engine during a test run.

6.2 The Delivered Product

The complete system is shown in Figure 6.2.1. Thirteen sensors are used to measure various measurements required to analyze the Brayton cycle of the gas turbine engine.

The system is easy to use, and can be operated with minimal training. The system is started by the push of a button, after which the system enters the startup procedure where it controls the solenoid valves, the glow plug, the starter motor, and the fuel flow. These parameters are controlled until the gas turbine engine reaches an idle state at 40 000 RPM. Once the idle state has been reached, the gas turbine engine can be controlled via the control potentiometer up to 120 000 RPM. The unit is stopped by the stop button, while the emergency button can be used if unwanted behavior occurs.

During the entire operation, data and events are logged and displayed on the PC and LCD display unit. The speed, temperature measurements, and pressure measurements are also plotted in real time on the PC display. Diagnostic LED's indicate the status of the solenoid valves and a diagnostics mode can be entered to verify and maintain the sensors and controls. This diagnostics mode is implemented in a wizard format to make it easy and simple to use.

Figure 6.2.1 The Micro Gas Turbine Measurement System

Two versions of the logging software are available. One consists of a GUI that shows the data in real time on the PC display while the other version only logs and save the data without displaying the information. The last mentioned software can be used to increase the sampling rate if a slow PC is used.

Safety features are incorporated and include automatic shutdown procedures if extended temperatures are reached or if the system becomes unstable. The unit is also mounted behind a Perspex safety panel, which should be closed during operation.

This unit enables the North West University to demonstrate the operation of the gas turbine engine and the Brayton cycle to students through visual interpretation. The logged data can also be analyzed and used for practical exercises. This shows that the initial goal was achieved (a dry run demonstration was held at the school for mechanical engineering with full acceptance).

The total development costs for this micro gas turbine measurement system is around R200,000-00 when labor cost is included. This is half of the cost of a similar system as supplied by Turbine Technologies. The reason why this system could be developed at a reduced cost is mainly due to the high level of intellectual property of these systems, together with the development of a less expensive, but appropriate, data acquisition system. If this system needs to be reproduced, the cost could be far less because development has been done and no additional development costs have to be incurred. The cost impact for this project can be found in Appendix A.

The actual benefit lies in the intellectual property and knowledge that was gained through this project that now resides at the NWU. The real benefit cannot be measured at this stage because student practicals and further research by using this system could not yet be executed and are scheduled for 2008.

6.3 The Systems Engineering Approach

The success of this project can mainly be ascribed to the use of the systems engineering approach followed throughout this project.

The key of this approach lies in the detailed functional analysis done in Chapter 3, consisting of the operational flow, system architecture, interface descriptions, and resource allocation. By making use of specific "design for" criteria, an optimal design was done, which resulted in a safe and usable system. This work thus showed how a functional analysis can be used to allocate requirements, identify design-critical functions and interfaces, and how to focus on specific aspects of design that were required in the initial stages of development.

During the XDM phase, a prototype was built to minimize initial technical risk. Thereafter an EDM was laid out on PCBs to finalize the design. The fact that a development phase was short-circuited (namely the ADM phase) serves to show the effectiveness of following a systems engineering approach.

Firmware and software were also written in the format of state flow diagrams that are traceable. This simplifies maintenance and supports further development of the system (if necessary).

6.4 The Way Forward

This gas turbine measurement system can be incorporated with Flownex®. Flownex® is a thermal-fluid network analysis program, enabling users to perform detail analysis of complex systems, such as gas turbines [13]. By integrating Flownex® with this measurement system, the actual measured data can be verified with the data generated by Flownex® for a similar model.

By integrating Flownex® with this measurement system, Flownex® can be used as a controller for the gas turbine measurement system. This would set the basis to show that Flownex® could be a real time controller for a plant through network analysis.

6.5 Conclusion

The measurement system for the micro gas turbine was successfully developed. That is, the system was designed, constructed, implemented, and tested. Sensors are available to measure speed, temperature, pressure, thrust, and fuel consumption. The measurements are shown on the control panel and displayed in real time on the PC. The PC also logs the data in spreadsheet format, enabling the user to analyze the data afterwards.

The system is easy to use with minimal training needed to operate the system. The design incorporates safety features due to high rotational speeds of the gas turbine engine. This micro gas turbine measurement system is developed at less than half of the cost of the existing system, without limiting any features or functionality.

Appendix

Appendix A: System Development Cost

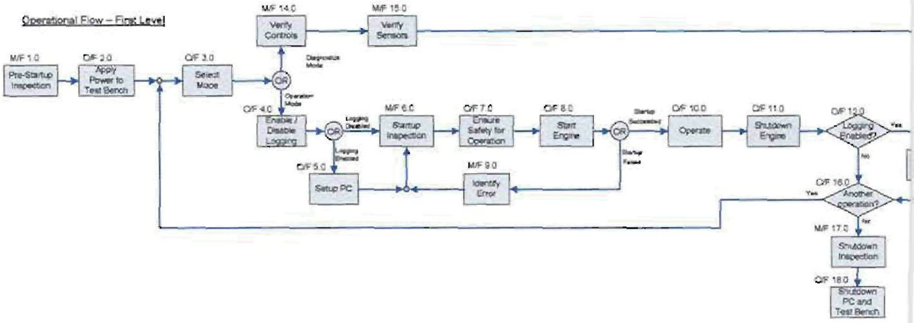
The cost impact for this project is shown in the table below.

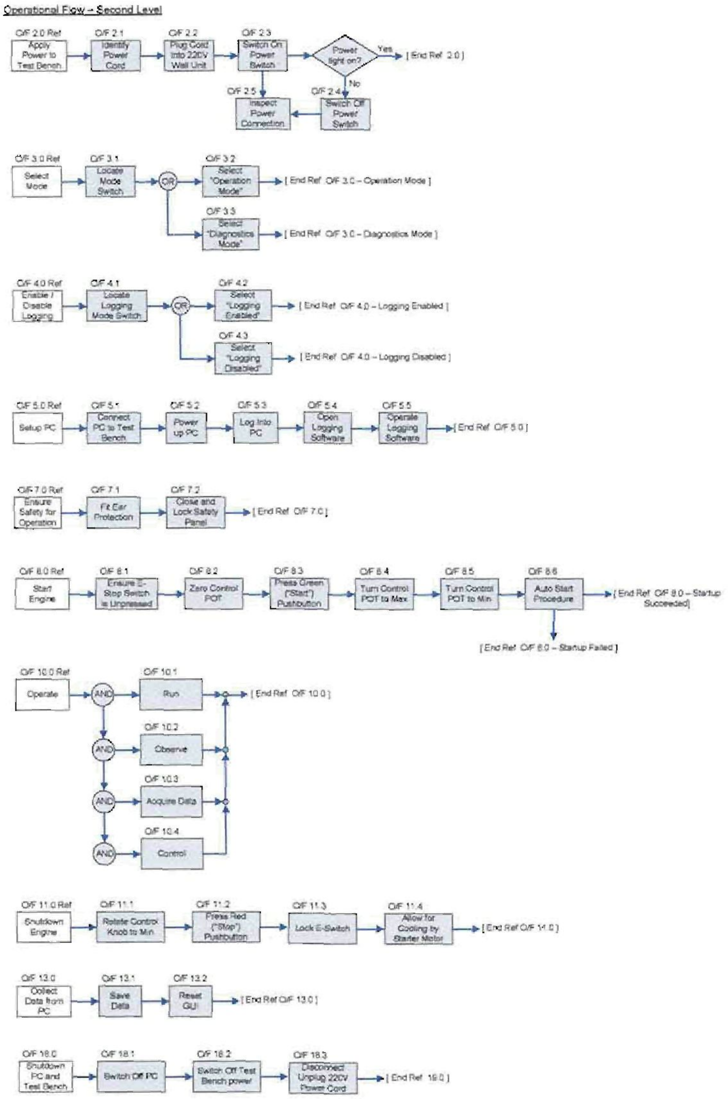
Table A.1 System Costs

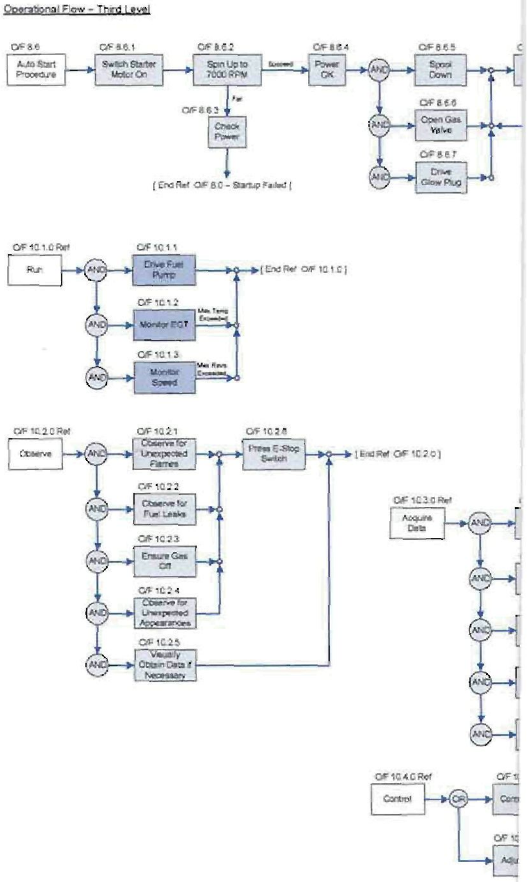
Category	**Description**	**Cost**
Mechanical	Gas Turbine Engine	ZAR 18,500.00
	Mechanical Structure	ZAR 3,600.00
	Stainless Steel Control Panel	ZAR 500.00
Electronic	Instrumentation	ZAR 15,300.00
	Wiring	ZAR 200.00
	PCB manufacturing	ZAR 1,400.00
	Electronic Components	ZAR 2,000.00
	Switch Mode PSU	ZAR 500.00
	Solenoid Valves and Fittings	ZAR 1,000.00
	Other	ZAR 5,000.00
Labor	Master's students (indirect)	ZAR 160,000
	Total	**ZAR 208,000.00**

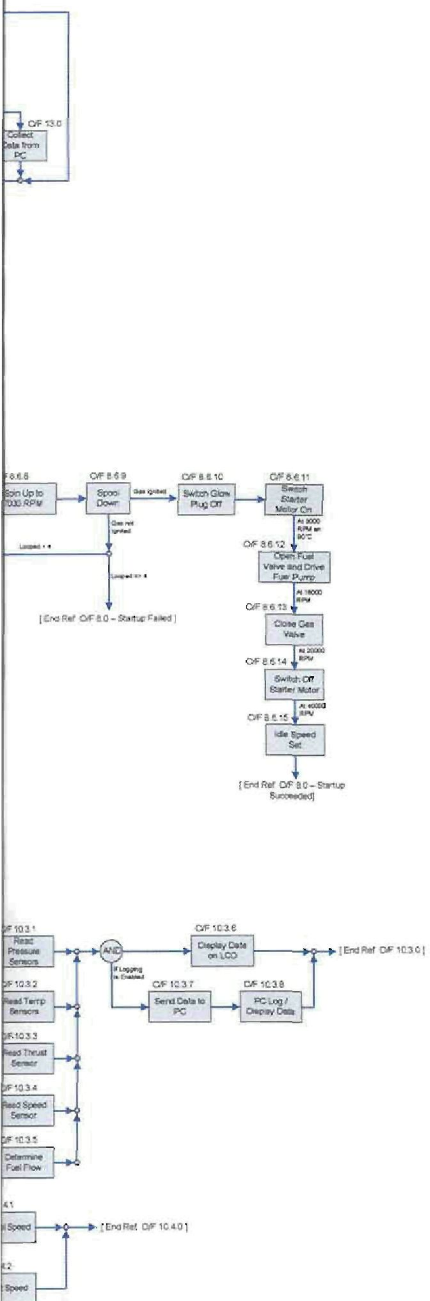
The direct product cost excludes development cost comes to ZAR 48,000. This excludes commercialization expenses, should this product be sold commercially.

Appendix B: Functional Analysis – System Functional Flow

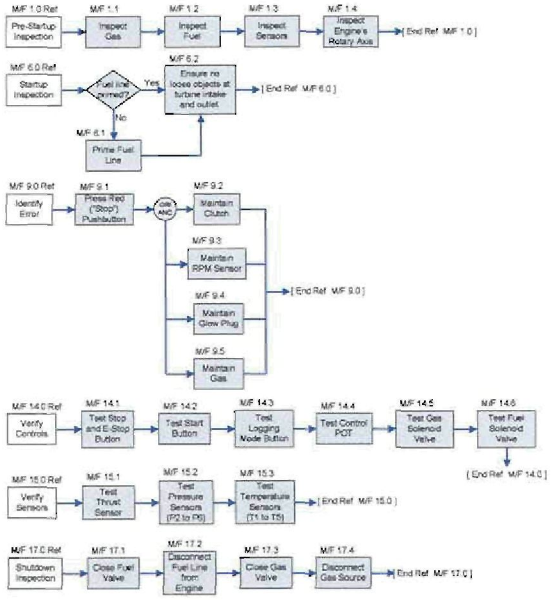

Operational Flow – First Level


Operational Flow – Second Level

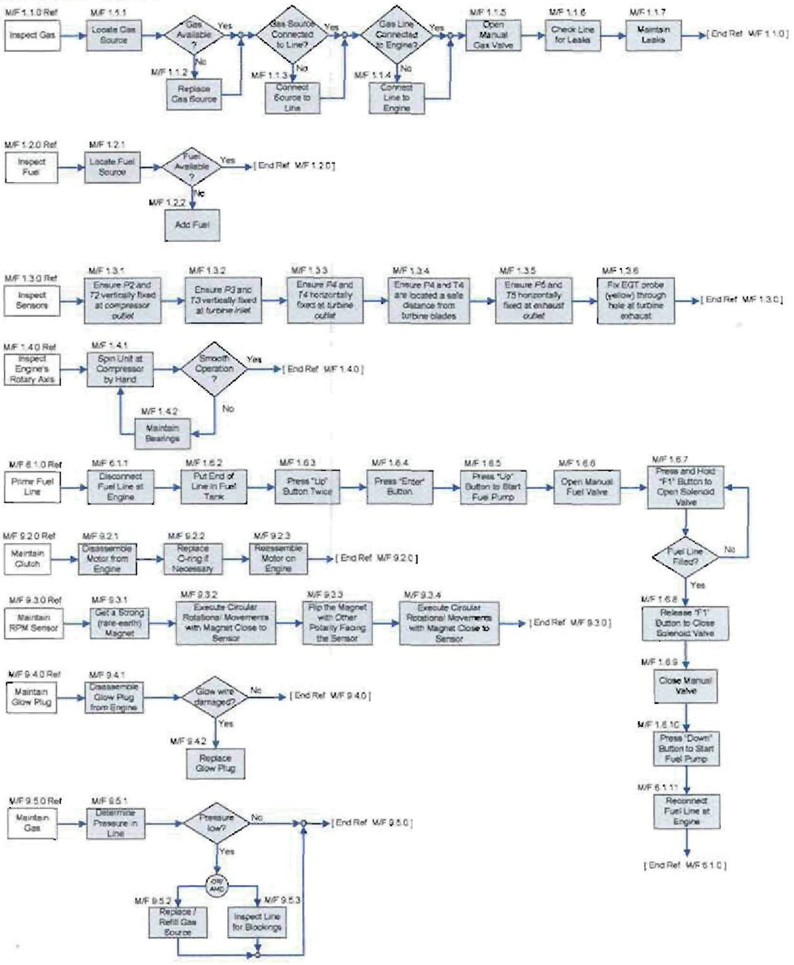

Operational Flow – Third Level



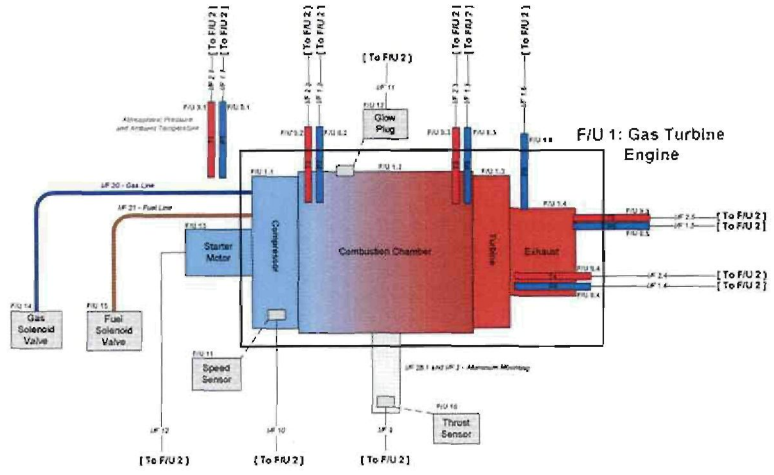
Maintenance Flow – Second Level

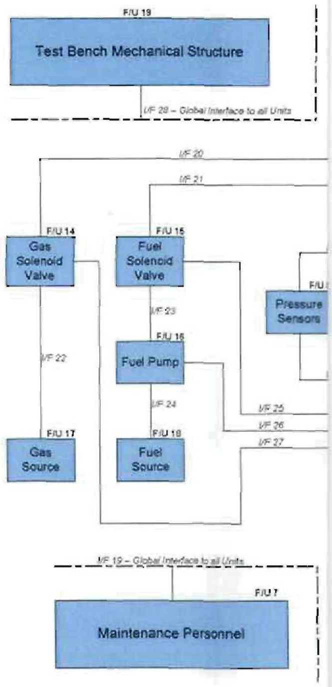


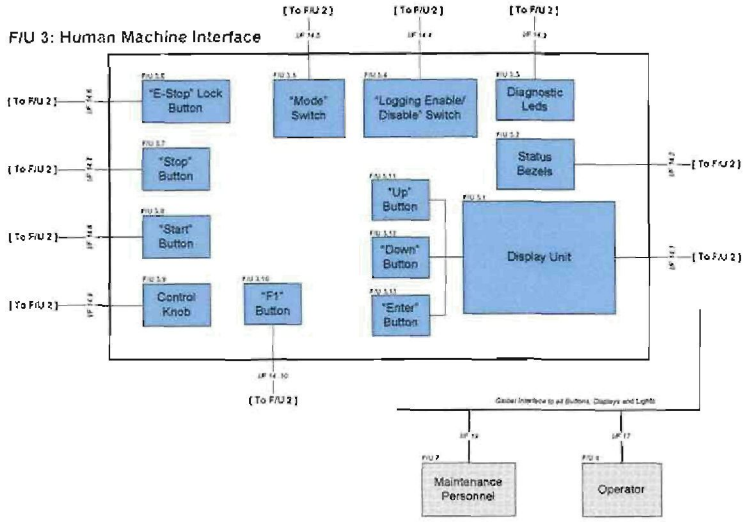
Maintenance Flow – Third Level

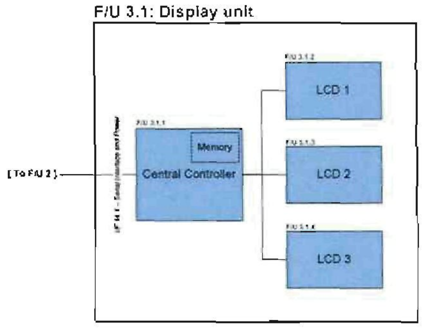


Appendix B: Functional Analysis – System Architecture

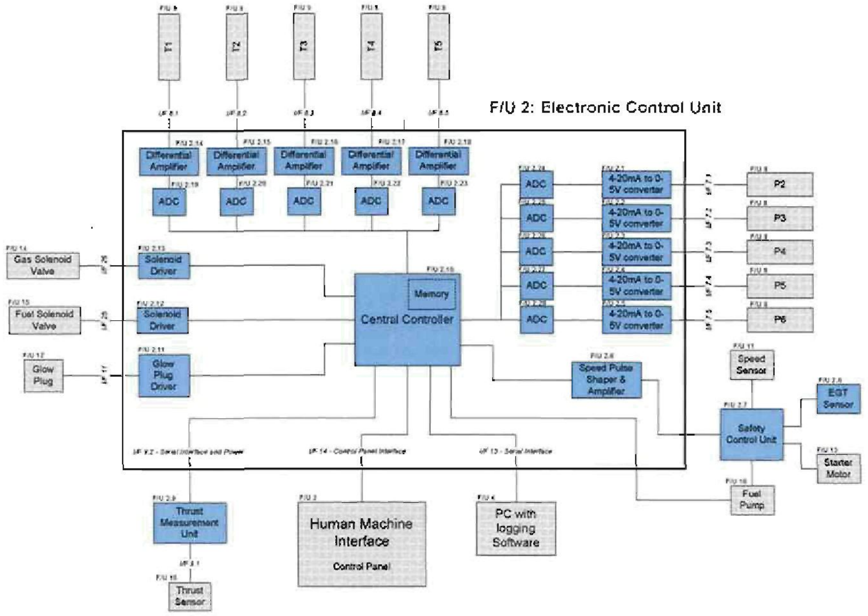


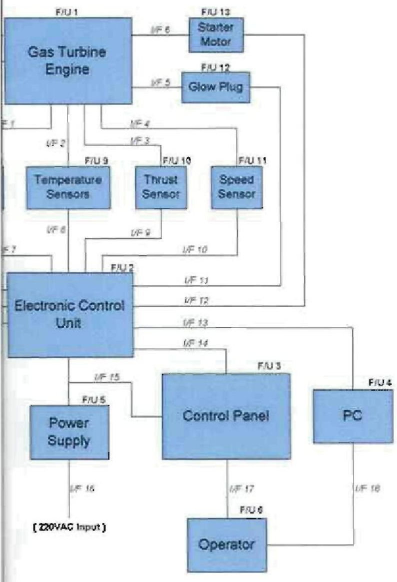




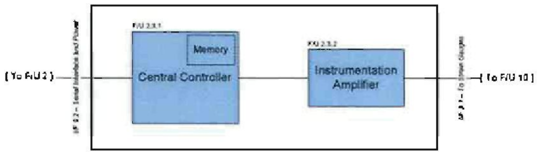


F/U 2: Electronic Control Unit

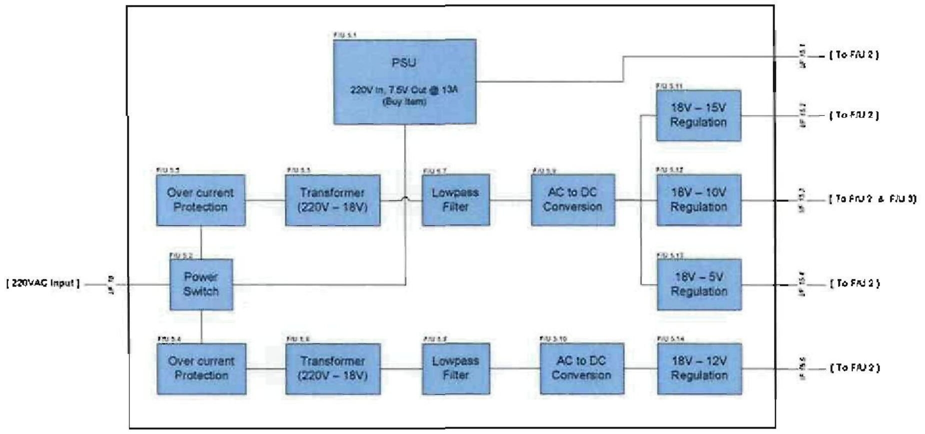




F/U 2.9: Thrust Measurement Unit



F/U 5: PSU (Power Supply Unit)



Appendix C: Schematics

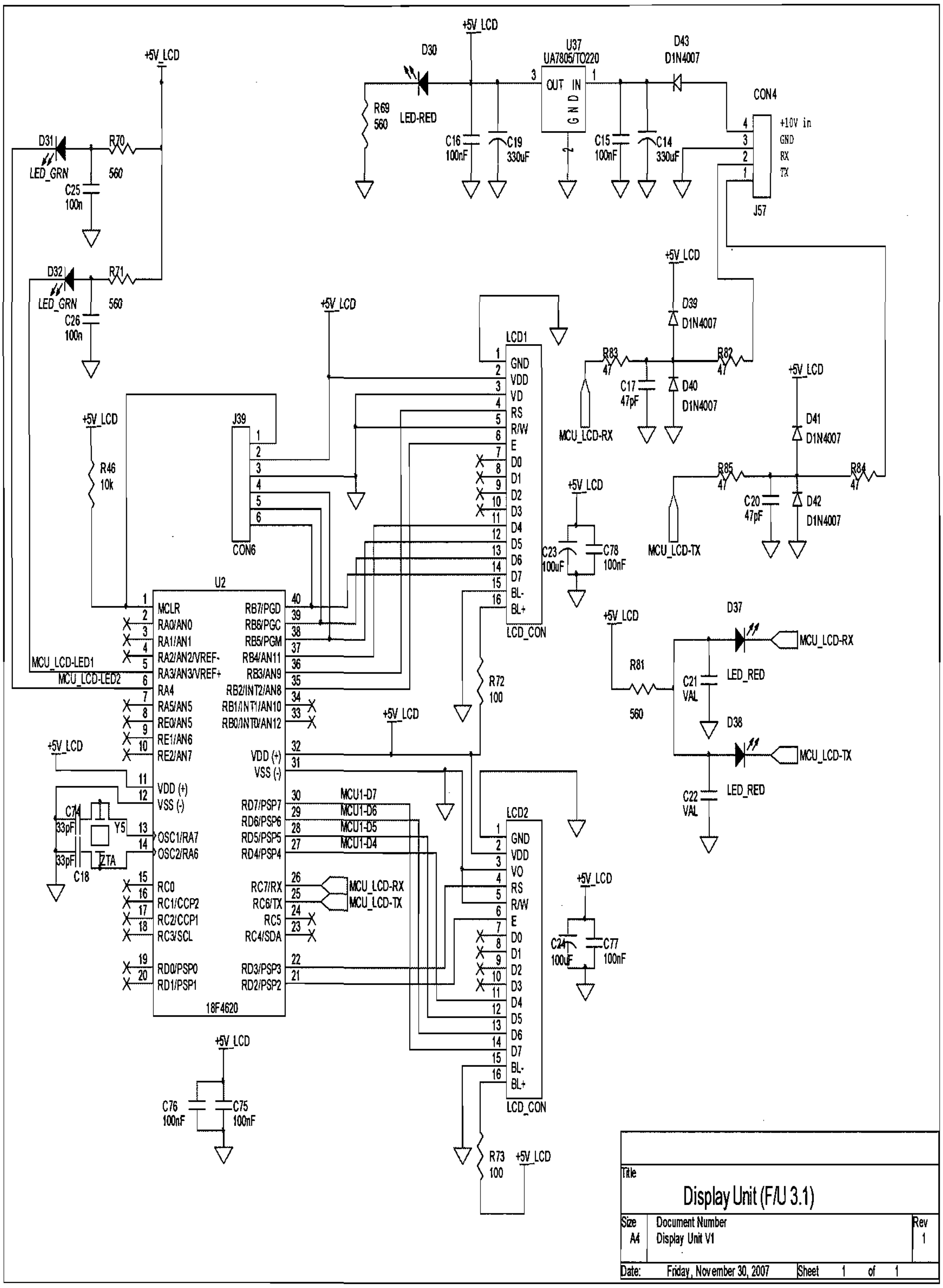


Figure C.1 Display Unit (F/U 3.1) Schematic

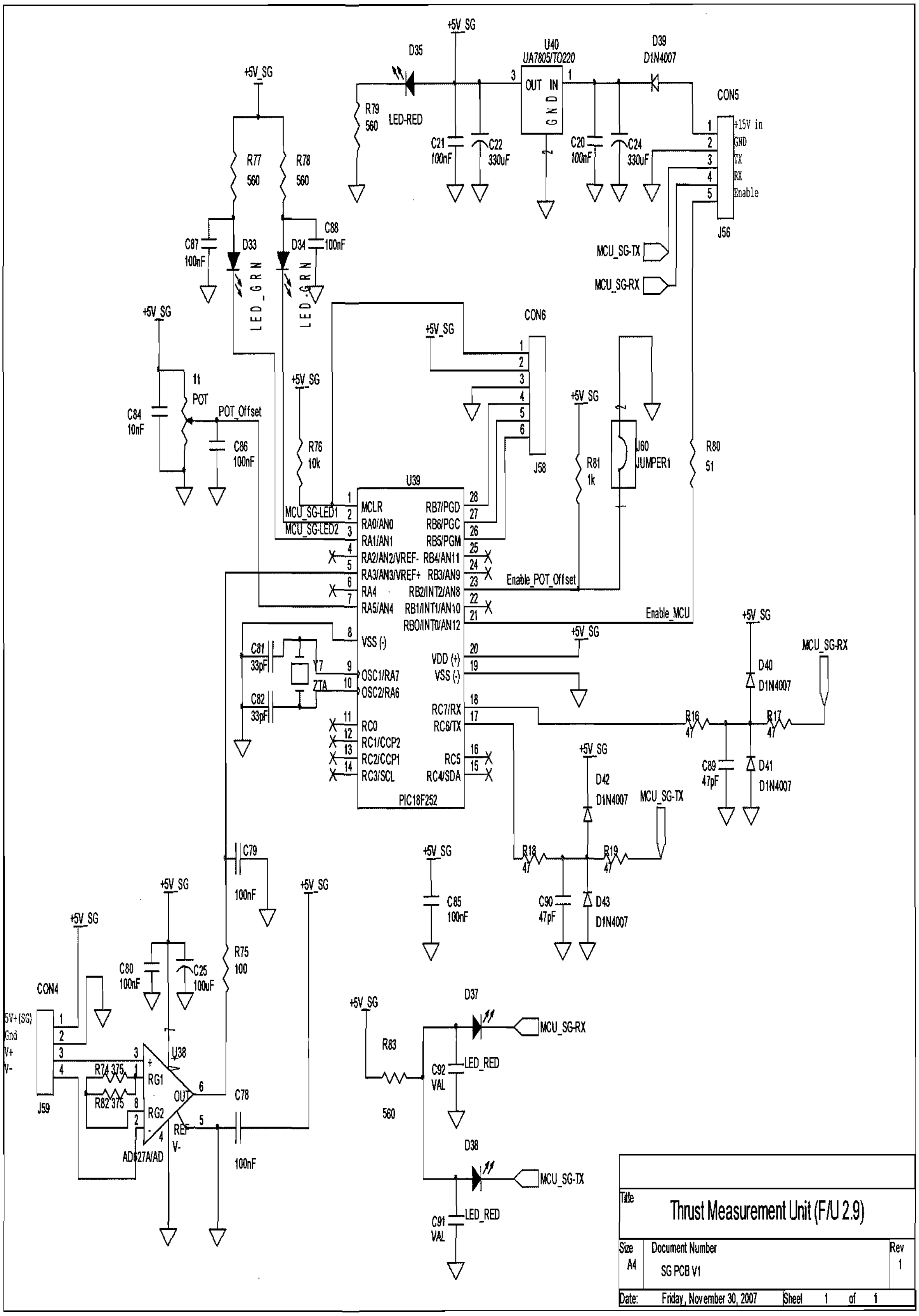


Figure C.2 Thrust Measurement Unit (F/U 2.9) Schematic

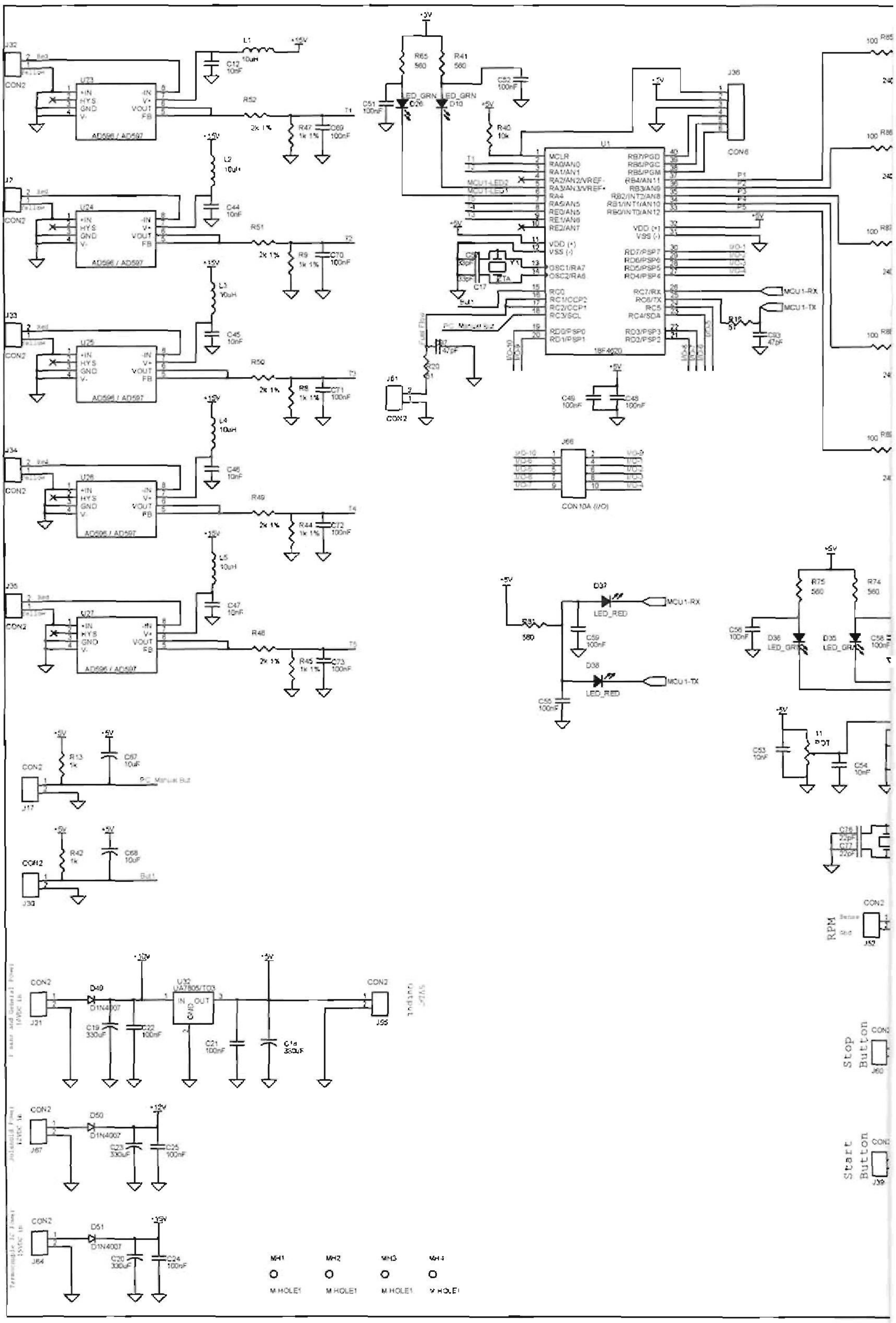
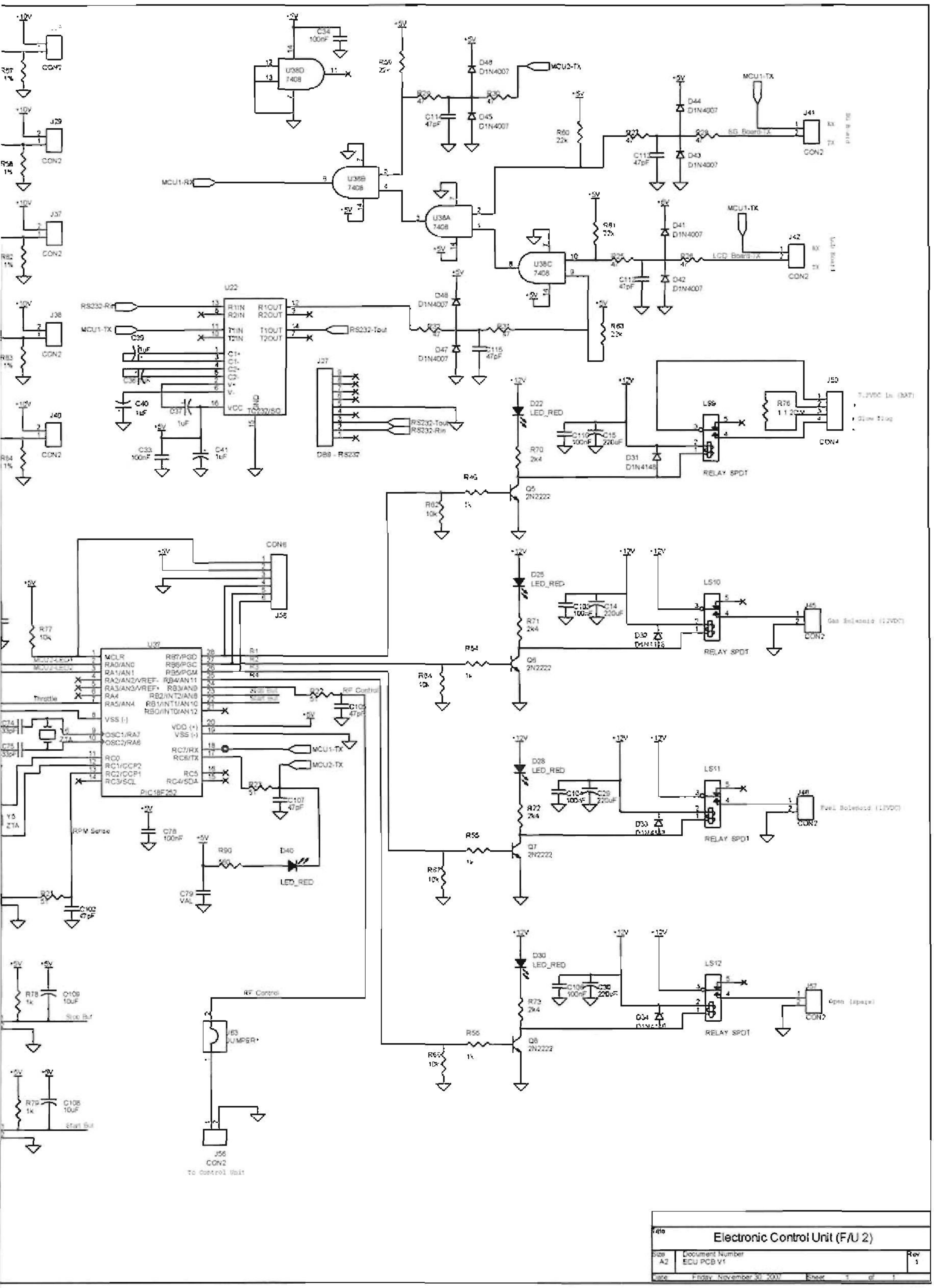


Figure C.3 Electro



nic Control Unit (F/U 2) Schematic

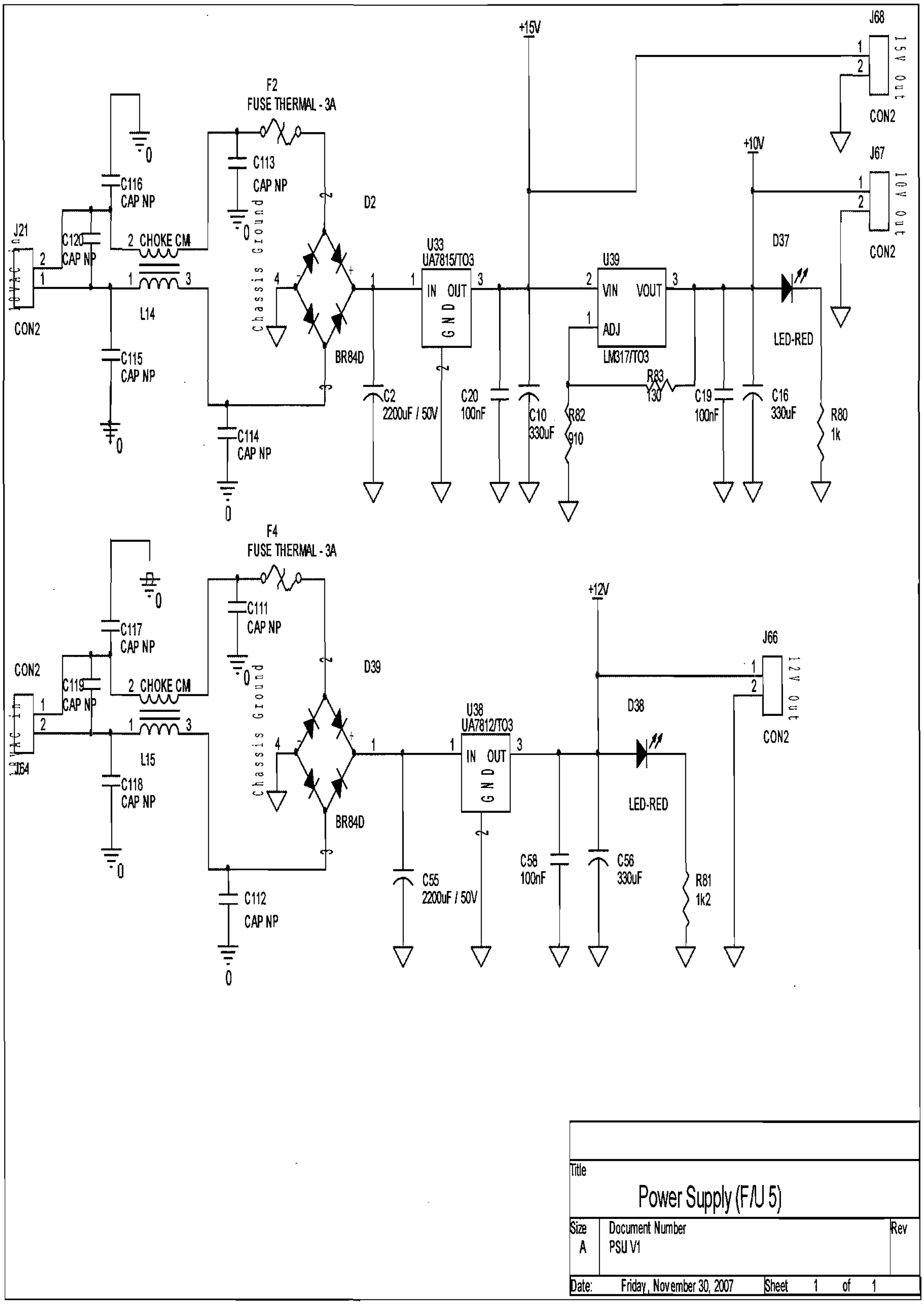


Figure C.4 Power Supply (F/U 5) Schematic

Appendix D: Results

The data logged with the alternative software during a separate test run is shown in **Error! Reference source not found.** to **Error! Reference source not found.**. The tabulated data for this test run can be found on the accompanying CD (see Appendix F).

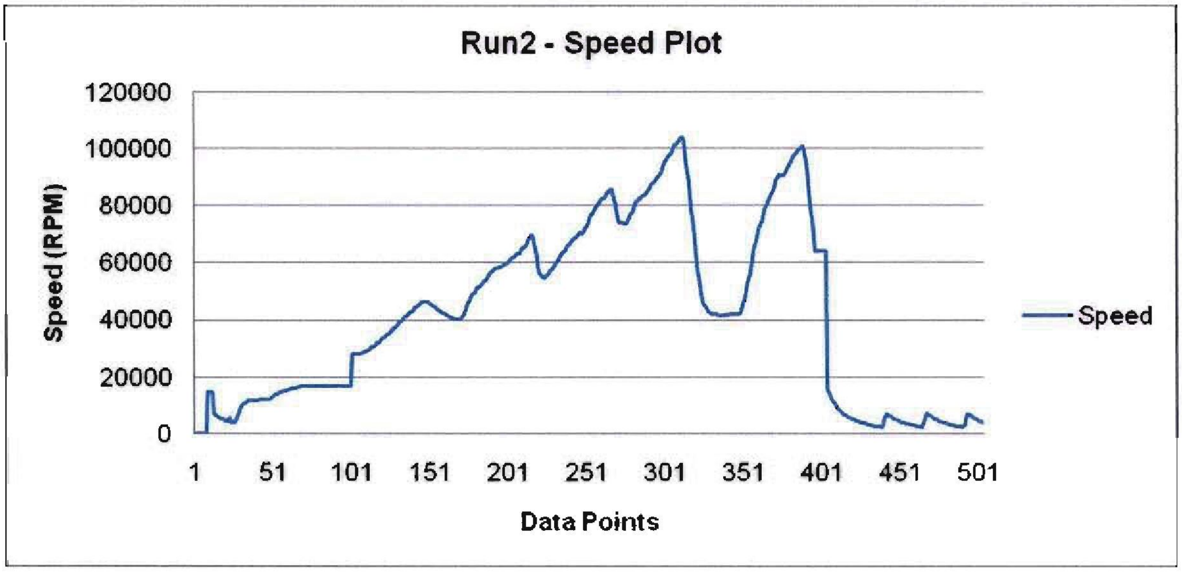


Figure D.1 The Speed Plot for Run2

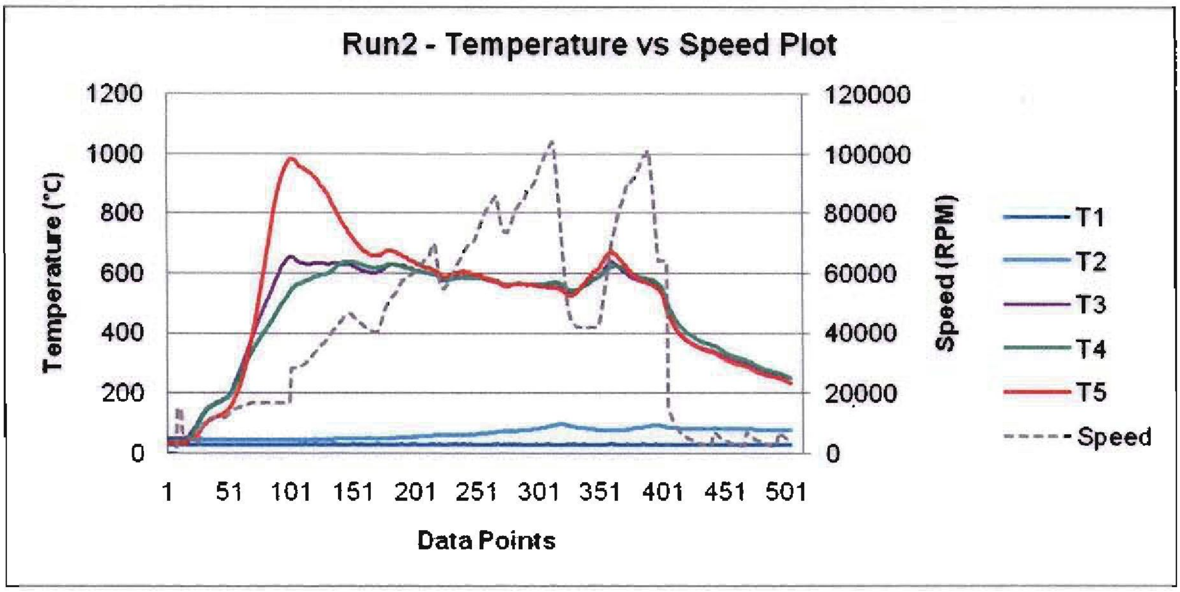


Figure D.2 The Temperature vs. Speed Plot for Run2

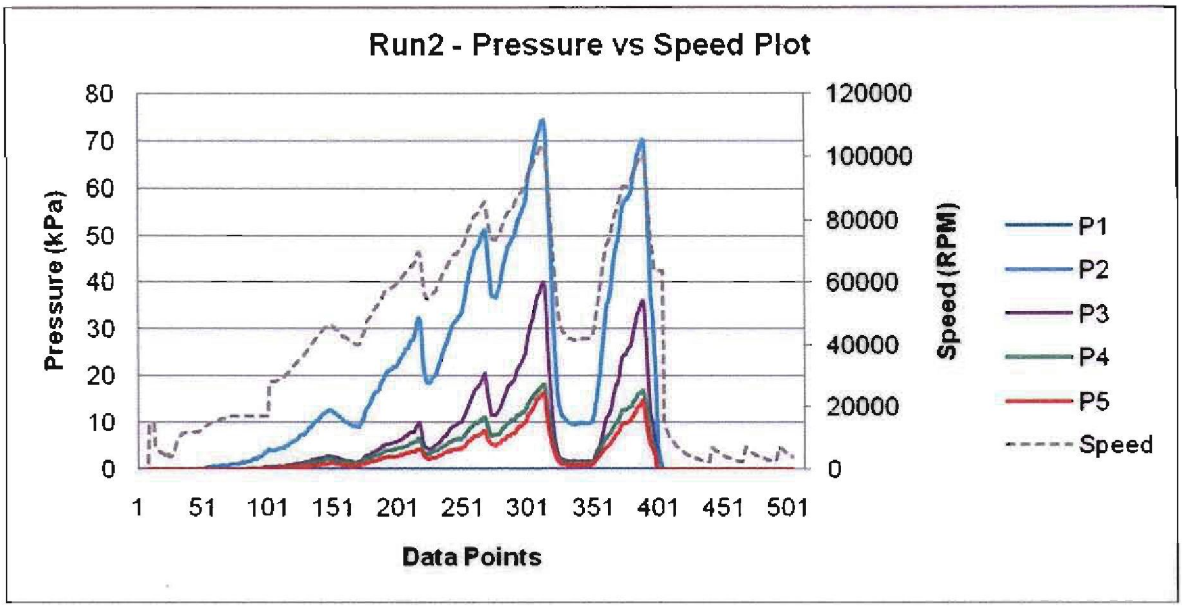


Figure D.3 The Pressure vs. Speed Plot for Run2

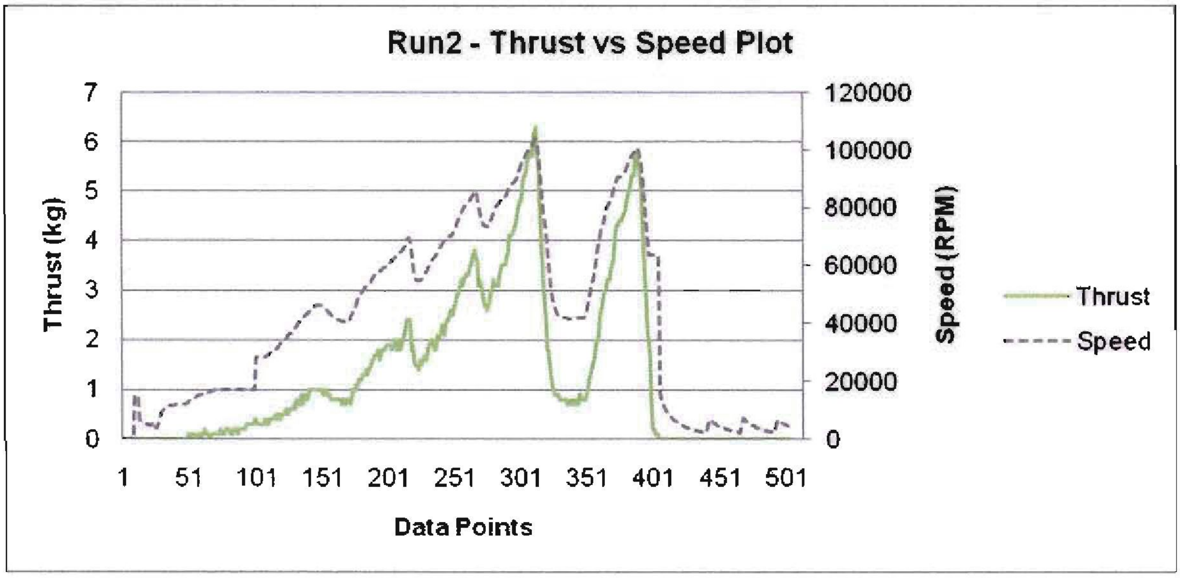


Figure D.4 The Thrust vs. Speed Plot for Run2

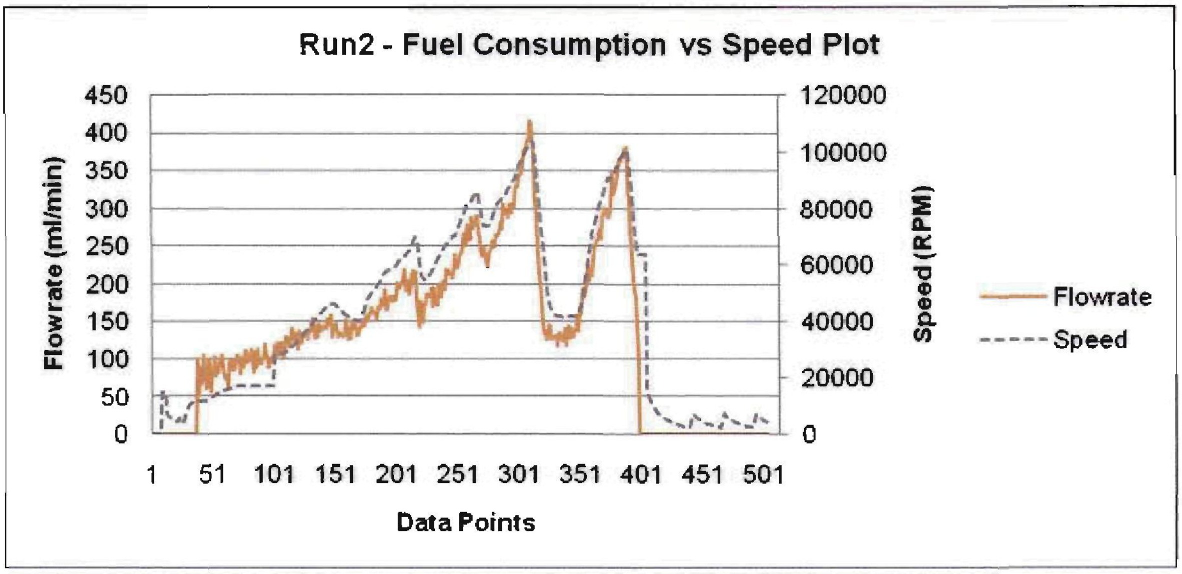
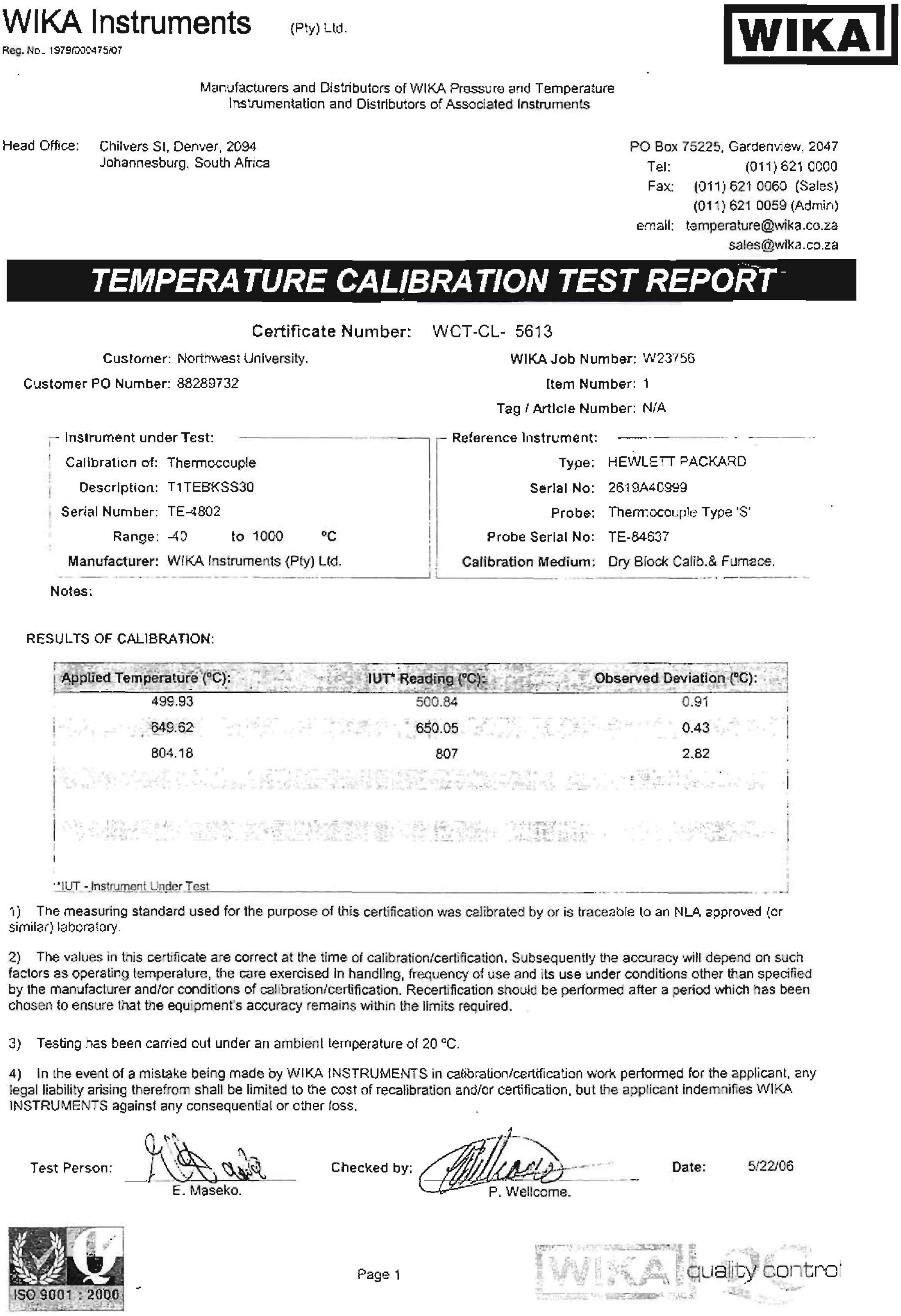


Figure D.5 The Fuel Consumption vs. Speed Plot for Run2

Appendix E: Calibration Certificates

The following pages show the calibration certificates for the thermocouple and pressure sensors from WIKA Instruments.



WIKA Instruments (Pty) Ltd.
Reg. No. 1979/000475/07

WIKA

Manufacturers and Distributors of WIKA Pressure and Temperature
Instrumentation and Distributors of Associated Instruments

Head Office: Chilvers St, Denver, 2094
Johannesburg, South Africa

PO Box 75225, Gardenview, 2047
Tel: (011) 621 0000
Fax: (011) 621 0060 (Sales)
(011) 621 0059 (Admin)
email: temperature@wika.co.za
sales@wika.co.za

TEMPERATURE CALIBRATION TEST REPORT

Certificate Number: WCT-CL- 5613

Customer: Northwest University.
WIKA Job Number: W23756
Customer PO Number: 88289732
Item Number: 1
Tag / Article Number: N/A

Instrument under Test:
Calibration of: Thermocouple
Description: T1TEBKSS30
Serial Number: TE-4802
Range: -40 to 1000 °C
Manufacturer: WIKA Instruments (Pty) Ltd.

Reference Instrument:
Type: HEWLETT PACKARD
Serial No: 2619A40999
Probe: Thermocouple Type 'S'
Probe Serial No: TE-84637
Calibration Medium: Dry Block Calib.& Furnace.

Notes:

RESULTS OF CALIBRATION:

Applied Temperature (°C):	IUT* Reading (°C):	Observed Deviation (°C):
499.93	500.84	0.91
649.62	650.05	0.43
804.18	807	2.82

*IUT - Instrument Under Test

1) The measuring standard used for the purpose of this certification was calibrated by or is traceable to an NLA approved (or similar) laboratory.

2) The values in this certificate are correct at the time of calibration/certification. Subsequently the accuracy will depend on such factors as operating temperature, the care exercised in handling, frequency of use and its use under conditions other than specified by the manufacturer and/or conditions of calibration/certification. Recertification should be performed after a period which has been chosen to ensure that the equipment's accuracy remains within the limits required.

3) Testing has been carried out under an ambient temperature of 20 °C.

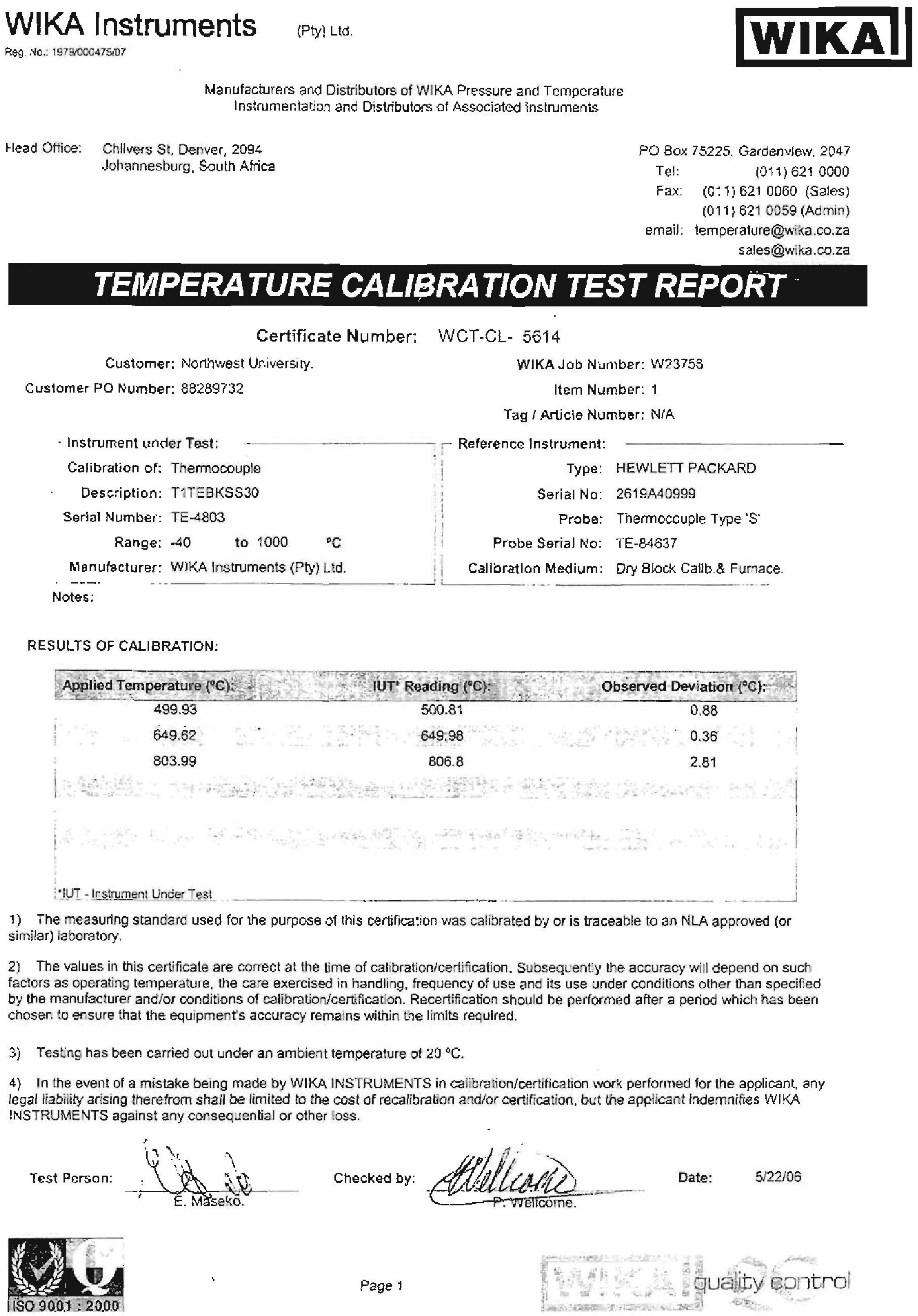
4) In the event of a mistake being made by WIKA INSTRUMENTS in calibration/certification work performed for the applicant, any legal liability arising therefrom shall be limited to the cost of recalibration and/or certification, but the applicant indemnifies WIKA INSTRUMENTS against any consequential or other loss.

Test Person: E. Maseko.
Checked by: P. Wellcome.
Date: 5/22/06

ISO 9001 : 2000

Page 1

WIKA quality control



WIKA Instruments (Pty) Ltd.

Reg. No.: 1979/000475/07

WIKA

Manufacturers and Distributors of WIKA Pressure and Temperature
Instrumentation and Distributors of Associated Instruments

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TEMPERATURE CALIBRATION TEST REPORT

Certificate Number: WCT-CL- 5614

Customer: Northwest University.

Customer PO Number: 88289732

WIKA Job Number: W23756

Item Number: 1

Tag / Article Number: N/A

Instrument under Test:

Calibration of: Thermocouple

Description: T1TEBKSS30

Serial Number: TE-4803

Range: -40 to 1000 °C

Manufacturer: WIKA Instruments (Pty) Ltd.

Reference Instrument:

Type: HEWLETT PACKARD

Serial No: 2619A40999

Probe: Thermocouple Type 'S'

Probe Serial No: TE-84637

Calibration Medium: Dry Block Calib.& Furnace.

Notes:

RESULTS OF CALIBRATION:

Applied Temperature (°C):	IUT* Reading (°C):	Observed Deviation (°C):
499.93	500.81	0.88
649.62	649.98	0.36
803.99	806.8	2.81

*IUT - Instrument Under Test

1) The measuring standard used for the purpose of this certification was calibrated by or is traceable to an NLA approved (or similar) laboratory.

2) The values in this certificate are correct at the time of calibration/certification. Subsequently the accuracy will depend on such factors as operating temperature, the care exercised in handling, frequency of use and its use under conditions other than specified by the manufacturer and/or conditions of calibration/certification. Recertification should be performed after a period which has been chosen to ensure that the equipment's accuracy remains within the limits required.

3) Testing has been carried out under an ambient temperature of 20 °C.

4) In the event of a mistake being made by WIKA INSTRUMENTS in calibration/certification work performed for the applicant, any legal liability arising therefrom shall be limited to the cost of recalibration and/or certification, but the applicant indemnifies WIKA INSTRUMENTS against any consequential or other loss.

Test Person: E. Maseko.

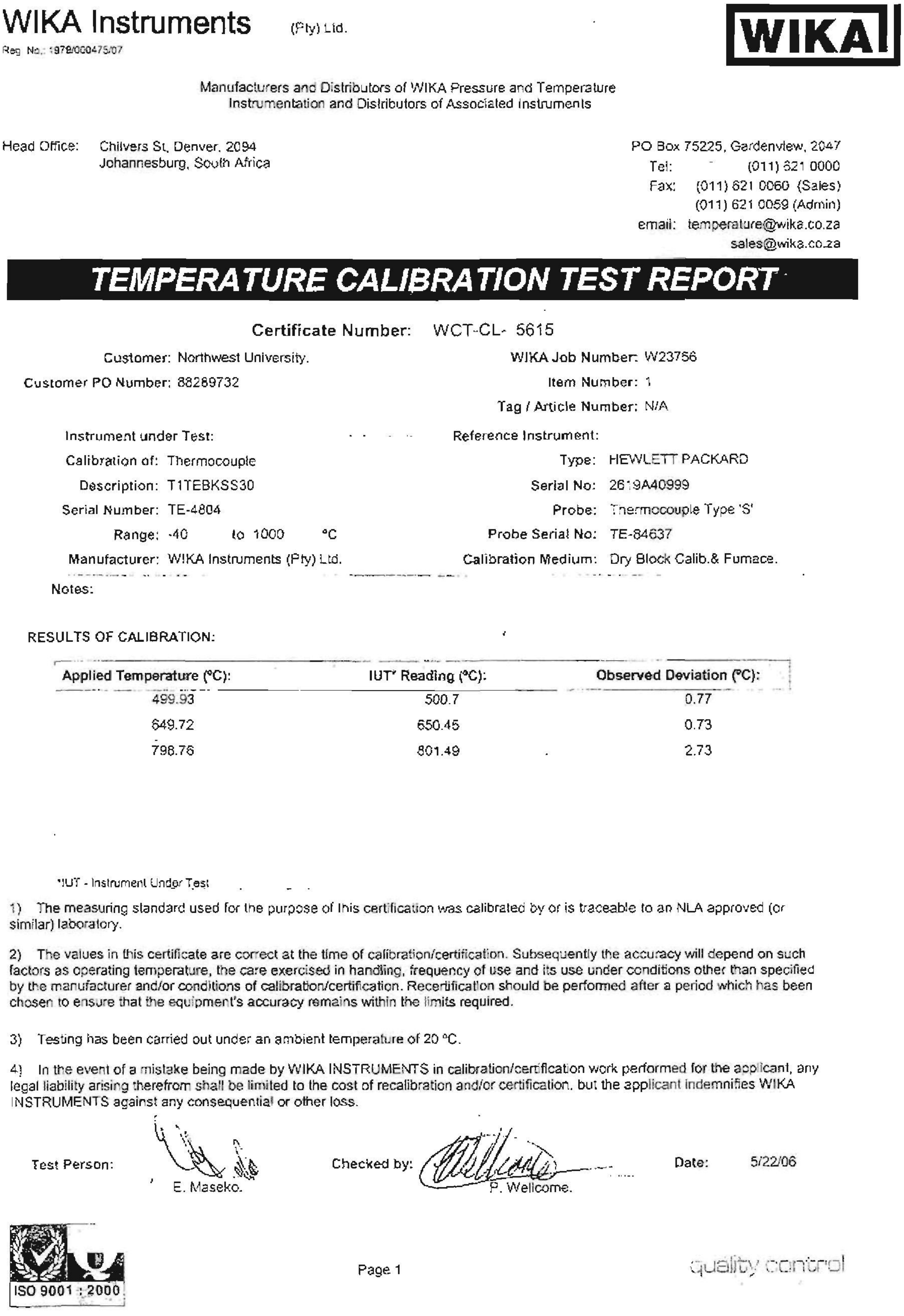
Checked by: P. Wellcome.

Date: 5/22/06

ISO 9001 : 2000

Page 1

WIKA quality control



WIKA Instruments (Pty) Ltd.
Reg. No.: 1978/000475/07

WIKA

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TEMPERATURE CALIBRATION TEST REPORT

Certificate Number: WCT-CL- 5615

Customer: Northwest University.
Customer PO Number: 88289732
WIKA Job Number: W23756
Item Number: 1
Tag / Article Number: N/A

Instrument under Test:
Calibration of: Thermocouple
Description: T1TEBKSS30
Serial Number: TE-4804
Range: -40 to 1000 °C
Manufacturer: WIKA Instruments (Pty) Ltd.

Reference Instrument:
Type: HEWLETT PACKARD
Serial No: 2619A40999
Probe: Thermocouple Type 'S'
Probe Serial No: TE-84637
Calibration Medium: Dry Block Calib.& Furnace.

Notes:

RESULTS OF CALIBRATION:

Applied Temperature (°C):	IUT* Reading (°C):	Observed Deviation (°C):
499.93	500.7	0.77
649.72	650.45	0.73
798.76	801.49	2.73

*IUT - Instrument Under Test

1) The measuring standard used for the purpose of this certification was calibrated by or is traceable to an NLA approved (or similar) laboratory.

2) The values in this certificate are correct at the time of calibration/certification. Subsequently the accuracy will depend on such factors as operating temperature, the care exercised in handling, frequency of use and its use under conditions other than specified by the manufacturer and/or conditions of calibration/certification. Recertification should be performed after a period which has been chosen to ensure that the equipment's accuracy remains within the limits required.

3) Testing has been carried out under an ambient temperature of 20 °C.

4) In the event of a mistake being made by WIKA INSTRUMENTS in calibration/certification work performed for the applicant, any legal liability arising therefrom shall be limited to the cost of recalibration and/or certification, but the applicant indemnifies WIKA INSTRUMENTS against any consequential or other loss.

Test Person: E. Maseko.

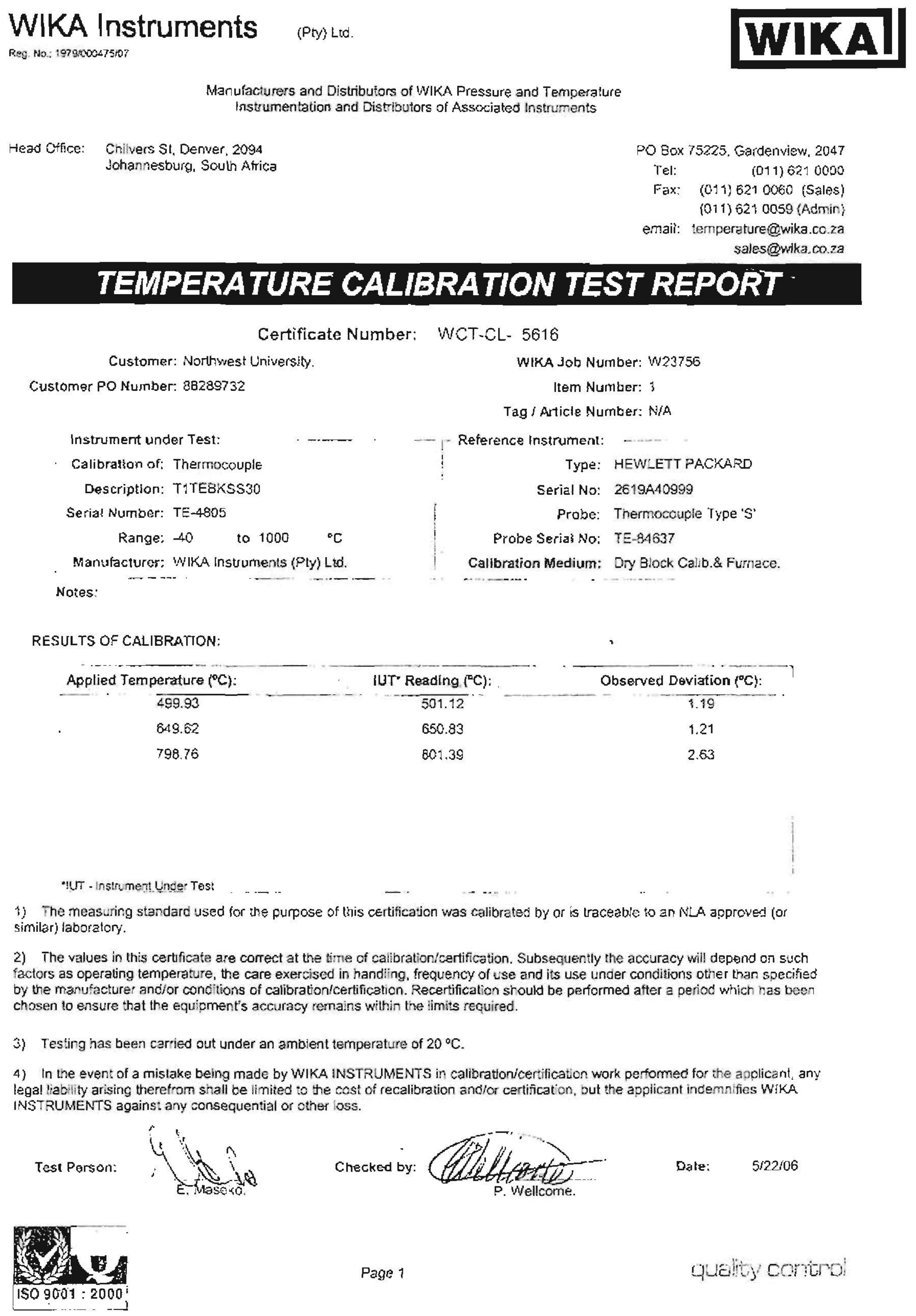
Checked by: P. Wellcome.

Date: 5/22/06

ISO 9001 : 2000

Page 1

quality control



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TEMPERATURE CALIBRATION TEST REPORT

Certificate Number: WCT-CL- 5616

Customer: Northwest University.
Customer PO Number: 88289732
WIKA Job Number: W23756
Item Number: 1
Tag / Article Number: N/A

Instrument under Test:
Calibration of: Thermocouple
Description: T1TE8KSS30
Serial Number: TE-4805
Range: -40 to 1000 °C
Manufacturer: WIKA Instruments (Pty) Ltd.

Reference Instrument:
Type: HEWLETT PACKARD
Serial No: 2619A40999
Probe: Thermocouple Type 'S'
Probe Serial No: TE-84637
Calibration Medium: Dry Block Calib.& Furnace.

Notes:

RESULTS OF CALIBRATION:

Applied Temperature (°C):	IUT* Reading (°C):	Observed Deviation (°C):
499.93	501.12	1.19
649.62	650.83	1.21
798.76	801.39	2.63

*IUT - Instrument Under Test

1) The measuring standard used for the purpose of this certification was calibrated by or is traceable to an NLA approved (or similar) laboratory.

2) The values in this certificate are correct at the time of calibration/certification. Subsequently the accuracy will depend on such factors as operating temperature, the care exercised in handling, frequency of use and its use under conditions other than specified by the manufacturer and/or conditions of calibration/certification. Recertification should be performed after a period which has been chosen to ensure that the equipment's accuracy remains within the limits required.

3) Testing has been carried out under an ambient temperature of 20 °C.

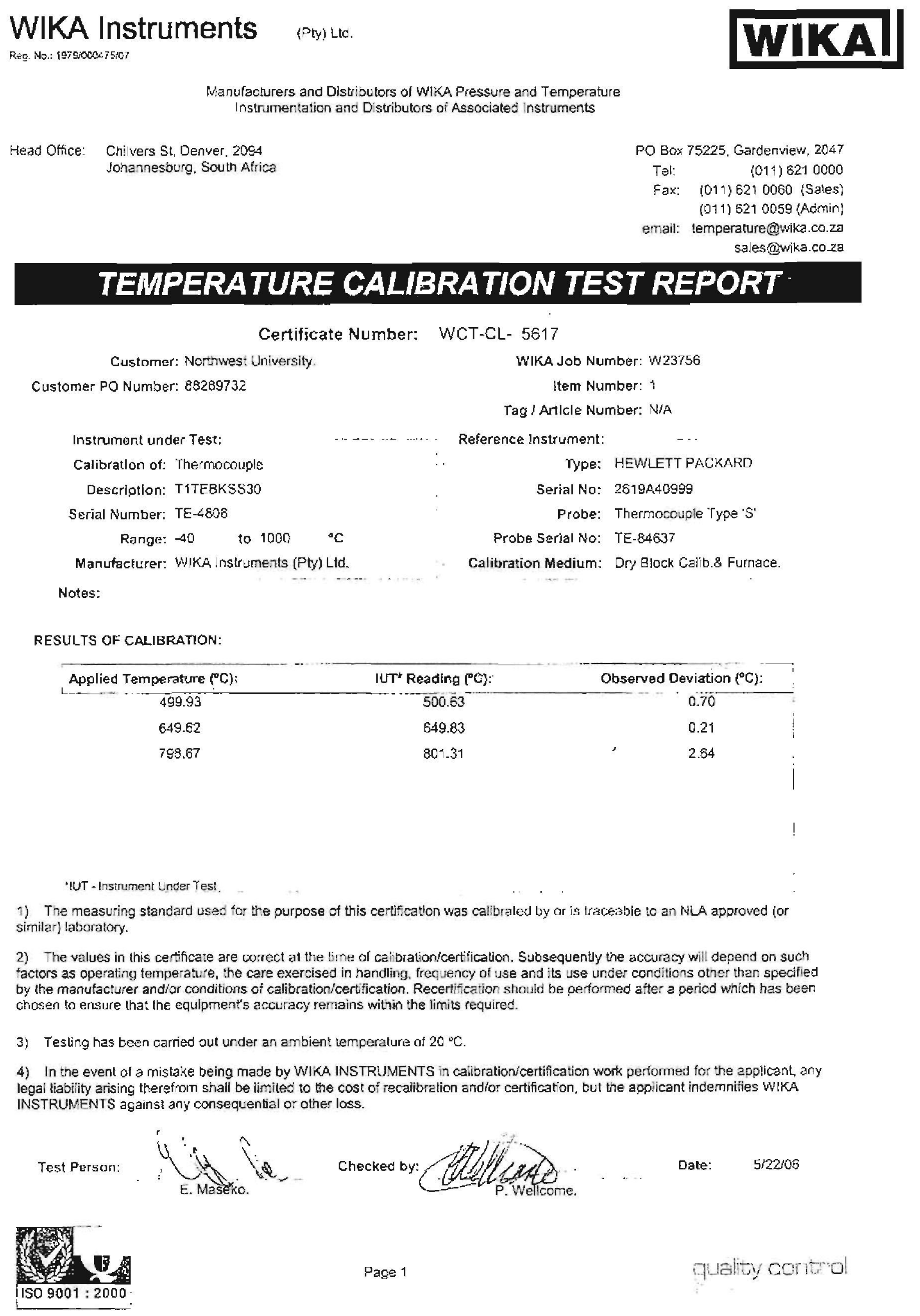
4) In the event of a mistake being made by WIKA INSTRUMENTS in calibration/certification work performed for the applicant, any legal liability arising therefrom shall be limited to the cost of recalibration and/or certification, but the applicant indemnifies WIKA INSTRUMENTS against any consequential or other loss.

Test Person: E. Maseko.
Checked by: P. Wellcome.
Date: 5/22/06

ISO 9001 : 2000

Page 1

quality control



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TEMPERATURE CALIBRATION TEST REPORT

Certificate Number: WCT-CL- 5617

Customer: Northwest University.
Customer PO Number: 88289732
WIKA Job Number: W23756
Item Number: 1
Tag / Article Number: N/A

Instrument under Test:
Calibration of: Thermocouple
Description: T1TEBKSS30
Serial Number: TE-4806
Range: -40 to 1000 °C
Manufacturer: WIKA Instruments (Pty) Ltd.

Reference Instrument:
Type: HEWLETT PACKARD
Serial No: 2619A40999
Probe: Thermocouple Type 'S'
Probe Serial No: TE-84637
Calibration Medium: Dry Block Calib.& Furnace.

Notes:

RESULTS OF CALIBRATION:

Applied Temperature (°C):	IUT* Reading (°C):	Observed Deviation (°C):
499.93	500.63	0.70
649.62	649.83	0.21
798.67	801.31	2.64

*IUT - Instrument Under Test.

1) The measuring standard used for the purpose of this certification was calibrated by or is traceable to an NLA approved (or similar) laboratory.

2) The values in this certificate are correct at the time of calibration/certification. Subsequently the accuracy will depend on such factors as operating temperature, the care exercised in handling, frequency of use and its use under conditions other than specified by the manufacturer and/or conditions of calibration/certification. Recertification should be performed after a period which has been chosen to ensure that the equipment's accuracy remains within the limits required.

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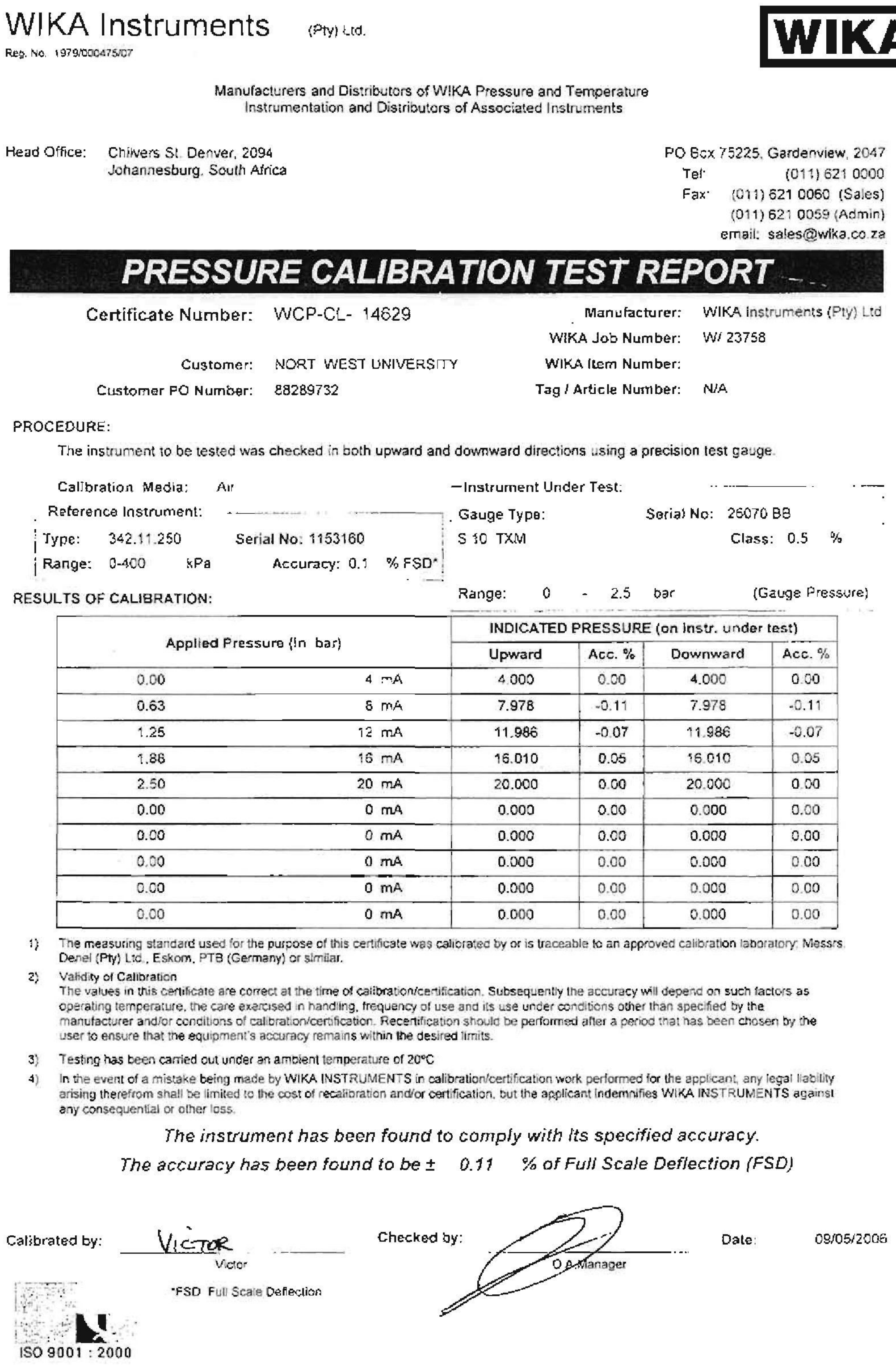
Test Person: E. Maseko.
Checked by: P. Wellcome.
Date: 5/22/06

ISO 9001 : 2000

Page 1

quality control



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PRESSURE CALIBRATION TEST REPORT

Certificate Number: WCP-CL- 14629
Customer: NORT WEST UNIVERSITY
Customer PO Number: 88289732

Manufacturer: WIKA Instruments (Pty) Ltd
WIKA Job Number: W/ 23758
WIKA Item Number:
Tag / Article Number: N/A

PROCEDURE:

The instrument to be tested was checked in both upward and downward directions using a precision test gauge.

Calibration Media: Air

Reference Instrument:
Type: 342.11.250 Serial No: 1153160
Range: 0-400 kPa Accuracy: 0.1 % FSD*

Instrument Under Test:
Gauge Type: S 10 TXM Serial No: 26070 BB
Class: 0.5 %
Range: 0 - 2.5 bar (Gauge Pressure)

RESULTS OF CALIBRATION:

Applied Pressure (In bar)		INDICATED PRESSURE (on instr. under test)			
		Upward	Acc. %	Downward	Acc. %
0.00	4 mA	4.000	0.00	4.000	0.00
0.63	8 mA	7.978	-0.11	7.978	-0.11
1.25	12 mA	11.986	-0.07	11.986	-0.07
1.88	16 mA	16.010	0.05	16.010	0.05
2.50	20 mA	20.000	0.00	20.000	0.00
0.00	0 mA	0.000	0.00	0.000	0.00
0.00	0 mA	0.000	0.00	0.000	0.00
0.00	0 mA	0.000	0.00	0.000	0.00
0.00	0 mA	0.000	0.00	0.000	0.00
0.00	0 mA	0.000	0.00	0.000	0.00

1) The measuring standard used for the purpose of this certificate was calibrated by or is traceable to an approved calibration laboratory: Messrs. Denel (Pty) Ltd., Eskom, PTB (Germany) or similar.

2) Validity of Calibration
The values in this certificate are correct at the time of calibration/certification. Subsequently the accuracy will depend on such factors as operating temperature, the care exercised in handling, frequency of use and its use under conditions other than specified by the manufacturer and/or conditions of calibration/certification. Recertification should be performed after a period that has been chosen by the user to ensure that the equipment's accuracy remains within the desired limits.

3) Testing has been carried out under an ambient temperature of 20°C

4) In the event of a mistake being made by WIKA INSTRUMENTS in calibration/certification work performed for the applicant, any legal liability arising therefrom shall be limited to the cost of recalibration and/or certification, but the applicant indemnifies WIKA INSTRUMENTS against any consequential or other loss.

The instrument has been found to comply with its specified accuracy.

The accuracy has been found to be ± 0.11 % of Full Scale Deflection (FSD)

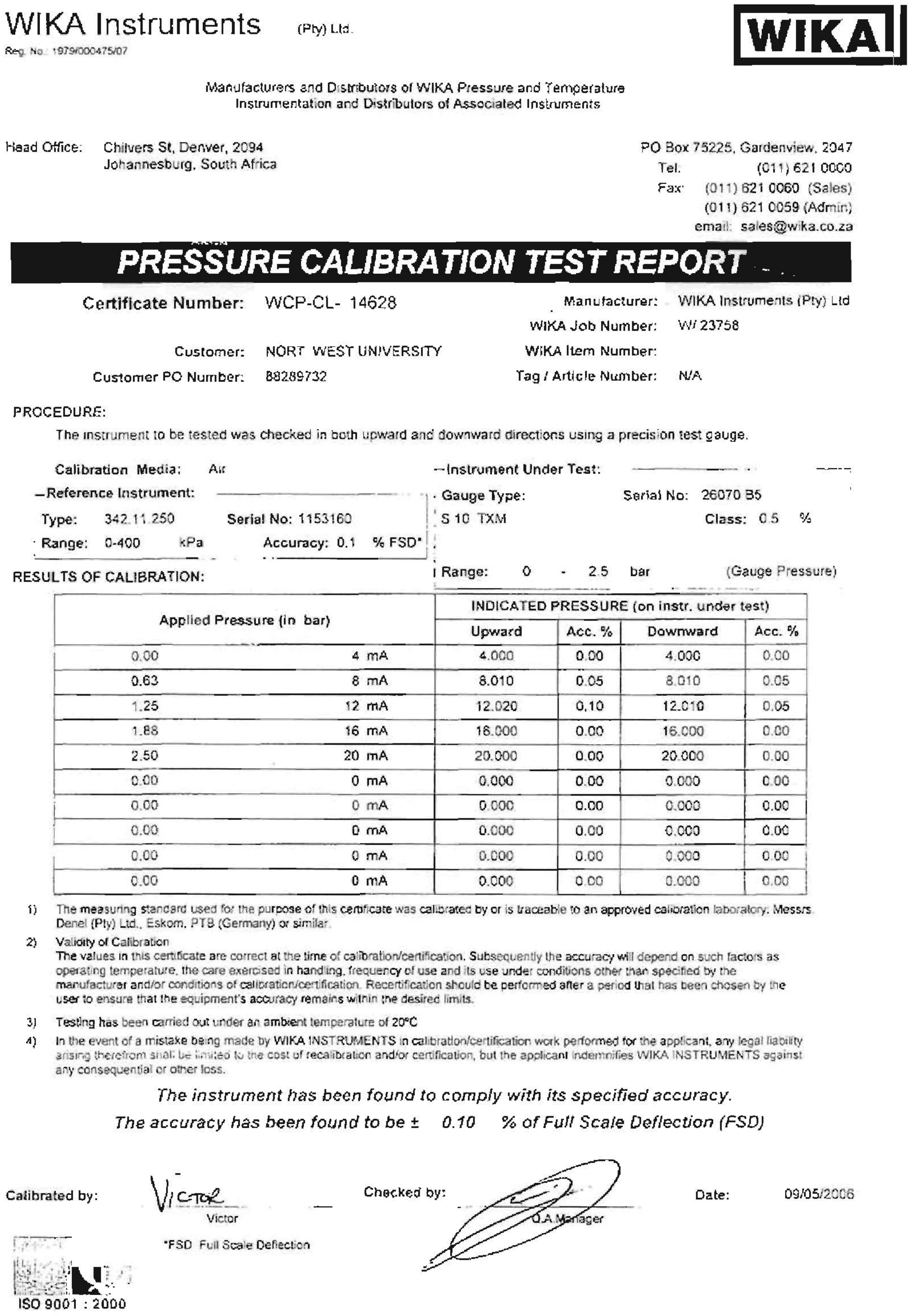
Calibrated by: VICTOR
Victor

Checked by:
Q.A. Manager

Date: 09/05/2006

*FSD Full Scale Deflection

ISO 9001 : 2000



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email: sales@wika.co.za

PRESSURE CALIBRATION TEST REPORT

Certificate Number: WCP-CL- 14628

Customer: NORT WEST UNIVERSITY
Customer PO Number: 88289732

Manufacturer: WIKA Instruments (Pty) Ltd
WIKA Job Number: W/ 23758
WIKA Item Number:
Tag / Article Number: N/A

PROCEDURE:

The instrument to be tested was checked in both upward and downward directions using a precision test gauge.

Calibration Media: Air

Reference Instrument:
Type: 342.11.250 **Serial No:** 1153160
Range: 0-400 kPa **Accuracy:** 0.1 % FSD*

Instrument Under Test:
Gauge Type: S 10 TXM **Serial No:** 26070 B5
Class: 0.5 %
Range: 0 - 2.5 bar (Gauge Pressure)

RESULTS OF CALIBRATION:

Applied Pressure (in bar)		INDICATED PRESSURE (on instr. under test)			
		Upward	Acc. %	Downward	Acc. %
0.00	4 mA	4.000	0.00	4.000	0.00
0.63	8 mA	8.010	0.05	8.010	0.05
1.25	12 mA	12.020	0.10	12.010	0.05
1.88	16 mA	16.000	0.00	16.000	0.00
2.50	20 mA	20.000	0.00	20.000	0.00
0.00	0 mA	0.000	0.00	0.000	0.00
0.00	0 mA	0.000	0.00	0.000	0.00
0.00	0 mA	0.000	0.00	0.000	0.00
0.00	0 mA	0.000	0.00	0.000	0.00
0.00	0 mA	0.000	0.00	0.000	0.00

1) The measuring standard used for the purpose of this certificate was calibrated by or is traceable to an approved calibration laboratory: Messrs. Denel (Pty) Ltd., Eskom, PTB (Germany) or similar.

2) Validity of Calibration
The values in this certificate are correct at the time of calibration/certification. Subsequently the accuracy will depend on such factors as operating temperature, the care exercised in handling, frequency of use and its use under conditions other than specified by the manufacturer and/or conditions of calibration/certification. Recertification should be performed after a period that has been chosen by the user to ensure that the equipment's accuracy remains within the desired limits.

3) Testing has been carried out under an ambient temperature of 20°C

4) In the event of a mistake being made by WIKA INSTRUMENTS in calibration/certification work performed for the applicant, any legal liability arising therefrom shall be limited to the cost of recalibration and/or certification, but the applicant indemnifies WIKA INSTRUMENTS against any consequential or other loss.

The instrument has been found to comply with its specified accuracy.

The accuracy has been found to be ± 0.10 % of Full Scale Deflection (FSD)

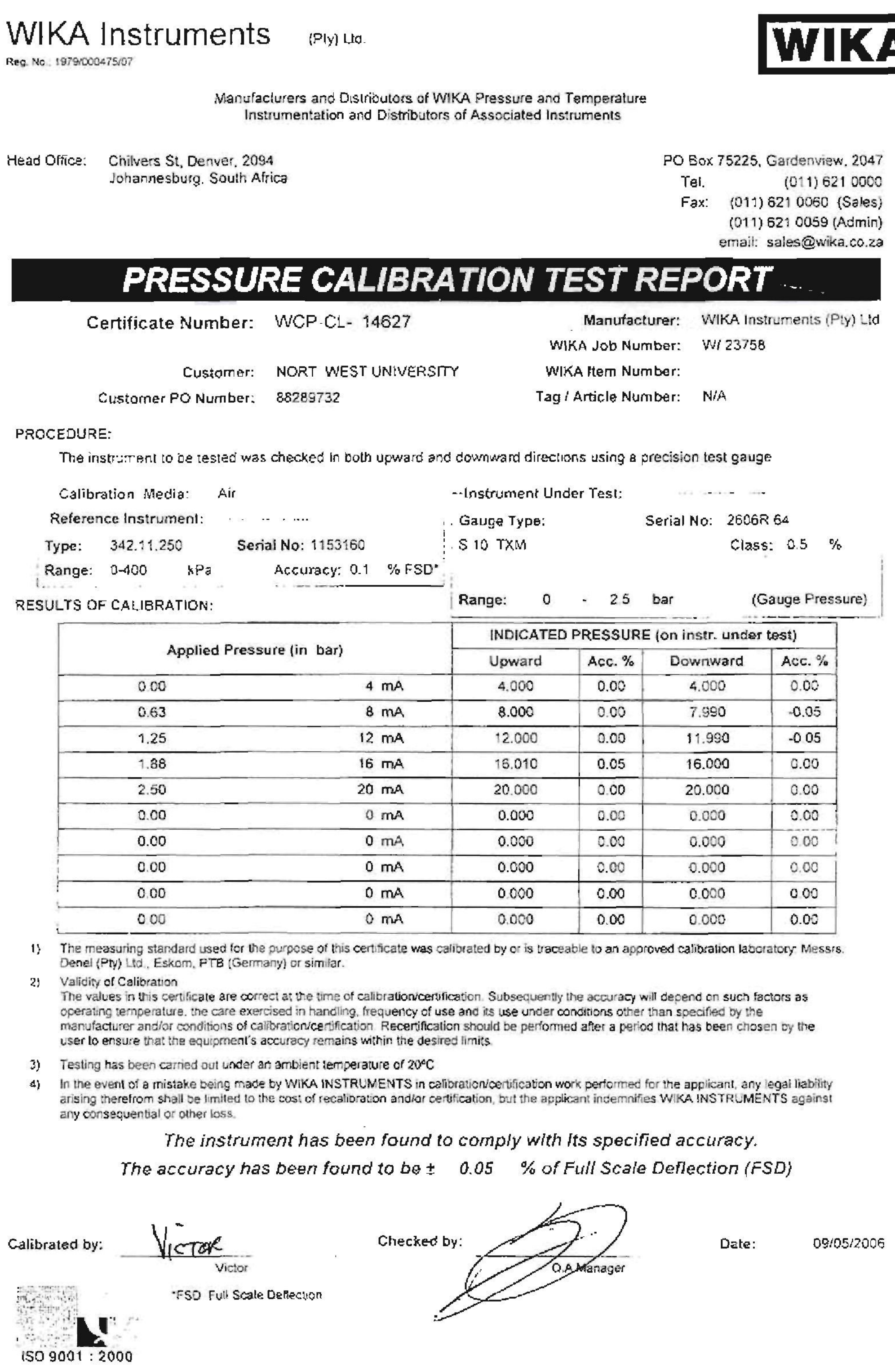
Calibrated by: Victor
Victor

Checked by:
Q.A Manager

Date: 09/05/2006

*FSD Full Scale Deflection

ISO 9001 : 2000



WIKA Instruments (Pty) Ltd.
Reg. No.: 1979/000475/07

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PRESSURE CALIBRATION TEST REPORT

Certificate Number: WCP-CL- 14627

Manufacturer: WIKA Instruments (Pty) Ltd
WIKA Job Number: W/ 23758
Customer: NORT WEST UNIVERSITY
WIKA Item Number:
Customer PO Number: 88289732
Tag / Article Number: N/A

PROCEDURE:

The instrument to be tested was checked in both upward and downward directions using a precision test gauge

Calibration Media: Air

Reference Instrument:
Type: 342.11.250
Serial No: 1153160
Range: 0-400 kPa
Accuracy: 0.1 % FSD*

Instrument Under Test:
Gauge Type: S 10 TXM
Serial No: 2606R 64
Class: 0.5 %
Range: 0 - 2.5 bar (Gauge Pressure)

RESULTS OF CALIBRATION:

Applied Pressure (in bar)		INDICATED PRESSURE (on instr. under test)			
		Upward	Acc. %	Downward	Acc. %
0.00	4 mA	4.000	0.00	4.000	0.00
0.63	8 mA	8.000	0.00	7.990	-0.05
1.25	12 mA	12.000	0.00	11.990	-0.05
1.88	16 mA	16.010	0.05	16.000	0.00
2.50	20 mA	20.000	0.00	20.000	0.00
0.00	0 mA	0.000	0.00	0.000	0.00
0.00	0 mA	0.000	0.00	0.000	0.00
0.00	0 mA	0.000	0.00	0.000	0.00
0.00	0 mA	0.000	0.00	0.000	0.00
0.00	0 mA	0.000	0.00	0.000	0.00

1) The measuring standard used for the purpose of this certificate was calibrated by or is traceable to an approved calibration laboratory: Messrs. Denel (Pty) Ltd., Eskom, PTB (Germany) or similar.

2) Validity of Calibration
The values in this certificate are correct at the time of calibration/certification. Subsequently the accuracy will depend on such factors as operating temperature, the care exercised in handling, frequency of use and its use under conditions other than specified by the manufacturer and/or conditions of calibration/certification. Recertification should be performed after a period that has been chosen by the user to ensure that the equipment's accuracy remains within the desired limits.

3) Testing has been carried out under an ambient temperature of 20°C

4) In the event of a mistake being made by WIKA INSTRUMENTS in calibration/certification work performed for the applicant, any legal liability arising therefrom shall be limited to the cost of recalibration and/or certification, but the applicant indemnifies WIKA INSTRUMENTS against any consequential or other loss.

The instrument has been found to comply with Its specified accuracy.

The accuracy has been found to be ± 0.05 % of Full Scale Deflection (FSD)

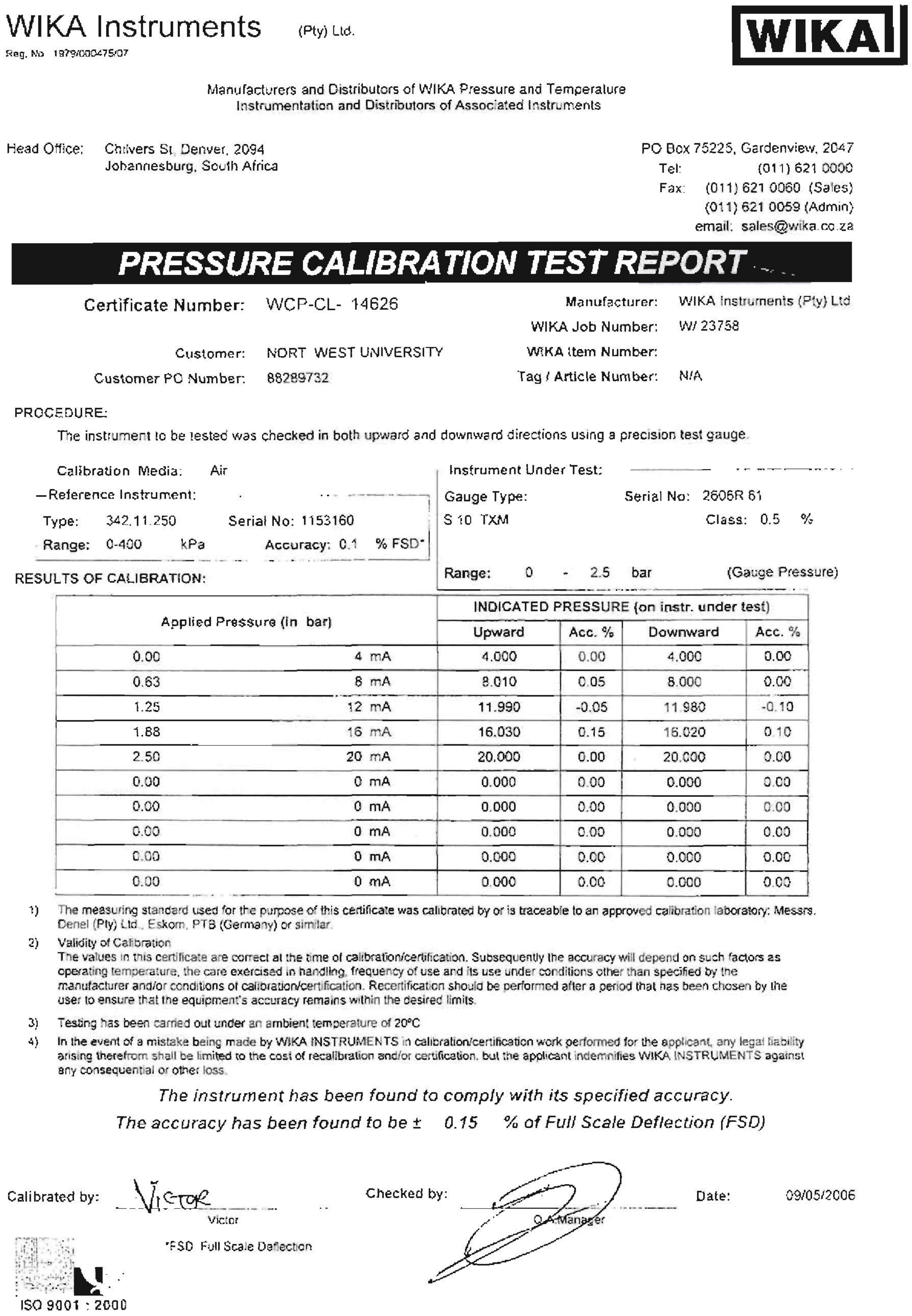
Calibrated by: Victor
Victor

Checked by:
Q.A Manager

Date: 09/05/2006

*FSD Full Scale Deflection

ISO 9001 : 2000



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PRESSURE CALIBRATION TEST REPORT

Certificate Number: WCP-CL- 14626

Manufacturer: WIKA Instruments (Pty) Ltd

WIKA Job Number: W/ 23758

Customer: NORT WEST UNIVERSITY

WIKA Item Number:

Customer PO Number: 88289732

Tag / Article Number: N/A

PROCEDURE:

The instrument to be tested was checked in both upward and downward directions using a precision test gauge.

Calibration Media: Air

Reference Instrument:

Type: 342.11.250 Serial No: 1153160

Range: 0-400 kPa Accuracy: 0.1 % FSD*

Instrument Under Test:

Gauge Type: Serial No: 2606R 61

S 10 TXM Class: 0.5 %

Range: 0 - 2.5 bar (Gauge Pressure)

RESULTS OF CALIBRATION:

Applied Pressure (in bar)		INDICATED PRESSURE (on instr. under test)			
		Upward	Acc. %	Downward	Acc. %
0.00	4 mA	4.000	0.00	4.000	0.00
0.63	8 mA	8.010	0.05	8.000	0.00
1.25	12 mA	11.990	-0.05	11.980	-0.10
1.88	16 mA	16.030	0.15	16.020	0.10
2.50	20 mA	20.000	0.00	20.000	0.00
0.00	0 mA	0.000	0.00	0.000	0.00
0.00	0 mA	0.000	0.00	0.000	0.00
0.00	0 mA	0.000	0.00	0.000	0.00
0.00	0 mA	0.000	0.00	0.000	0.00
0.00	0 mA	0.000	0.00	0.000	0.00

1) The measuring standard used for the purpose of this certificate was calibrated by or is traceable to an approved calibration laboratory: Messrs. Denel (Pty) Ltd., Eskom, PTB (Germany) or similar.

2) Validity of Calibration
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3) Testing has been carried out under an ambient temperature of 20°C

4) In the event of a mistake being made by WIKA INSTRUMENTS in calibration/certification work performed for the applicant, any legal liability arising therefrom shall be limited to the cost of recalibration and/or certification, but the applicant indemnifies WIKA INSTRUMENTS against any consequential or other loss.

The instrument has been found to comply with its specified accuracy.

The accuracy has been found to be ± 0.15 % of Full Scale Deflection (FSD)

Calibrated by: VICTOR
Victor

Checked by:
Q.A.Manager

Date: 09/05/2006

*FSD Full Scale Deflection

ISO 9001 : 2000

Appendix F: Data CD

F-1: Firmware Code

F-2: Software (MATLAB®) Code

F-3: OrCAD® PCB Designs

F-4: Results (Run1 and Run2)

F-5: Photos and video

F-6: Documentation

Bibliography

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